National Library of Canada
Acquisitions and Bibliographic Services Branch
395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale du Canada
Direction des acquisitions et des services bibliographiques
395, rue Wellington
Ottawa (Ontario)
K1A 0N4

Your file Votre référence

Our file Notre référence

NOTICE

The quality of this microform is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30, and subsequent amendments.

AVIS

La qualité de cette microforme dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30, et ses amendements subséquents.

Canada

UNIVERSITY OF ALBERTA

HEAT AND MASS TRANSFER DURING VASCULAR INFUSION OF BEEF CARCASSES

BY

YIWEI WANG

©

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN

PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

FOOD ENGINEERING

DEPARTMENT OF FOOD SCIENCE AND NUTRITION

EDMONTON, ALBERTA

Spring, 1994

National Library of Canada
Acquisitions and Bibliographic Services Branch
395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale du Canada
Direction des acquisitions et des services bibliographiques
395, rue Wellington
Ottawa (Ontario)
K1A 0N4

Your file Votre référence

Our file Notre référence

The author has granted an irrevocable non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of his/her thesis by any means and in any form or format, making this thesis available to interested persons.

L'auteur a accordé une licence irrévocable et non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de sa thèse de quelque manière et sous quelque forme que ce soit pour mettre des exemplaires de cette thèse à la disposition des personnes intéressées.

The author retains ownership of the copyright in his/her thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without his/her permission.

L'auteur conserve la propriété du droit d'auteur qui protège sa thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

ISBN 0-612-11411-2

Canada

UNIVERSITY OF ALBERTA

Release Form

NAME OF AUTHOR:

Yiwei Wang

TITLE OF THESIS:

Heat and Mass Transfer during Vascular Infusion of Beef Carcasses

DEGREE FOR WHICH THESIS WAS PRESENTED: **Master of Science**

YEAR THIS DEGREE GRANTED: **Spring 1994**

Permission is hereby granted to the UNIVERSITY OF ALBERTA LIBRARY to reproduce single copies of this thesis and to lend or sell such copies for private, scholarly or scientific research purposes only.

The author reserves other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without the author's written permission.

(SIGNED) Yiwei Wang

PERMANENT ADDRESS: #202, 10726-85 Ave.
Edmonton, Alberta
Canada, T6E, 2K8

Date: Dec. 23, 93

UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **HEAT AND MASS TRANSFER DURING VASCULAR INFUSION OF BEEF CARCASSES** submitted by **YIWEI WANG** in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** in **FOOD ENGINEERING.**

Dr. R. R. Segado

Dr. S. D. M. Jones

Dr. L. Ozimek

Dr. J. J. R. Feddes

Date: 17/ Dec /1993

ABSTRACT

The main objective of this study was to quantify and model mass and thermal energy transfer in intact beef carcasses undergoing chilling by vascular infusion of water. Intact beef carcasses were infused for several minutes by pumping pre-chilled water into the left carotid artery using a catheter. The resulting plasma and water effluent was drained from the jugular veins and collected. Carcasses were then conventionally dressed and further chilled in a chiller with air at 1°C and 1 m/s velocity.

During the infusion process, the water flowrate, inlet pressure, carcass weight, and the inlet and outlet fluid temperatures were monitored. The inlet water temperature was maintained at either 1 or 10°C; medium flowrate ranged from 12 to 17 l/min; and the total infused water was limited to either 10% or 20% of the animal live weight. During subsequent chilling, muscle temperature at several points within the carcass was monitored over 24 h.

The rate of temperature decline in the *longissimus dorsi* (LD) muscle was much greater than in carcasses chilled by conventional means. However, vascular infusion had no significant effect on the chilling rate of *semimembranosus* (SM) muscle at its maximum depth. Moreover, within the range of flowrates considered, muscle chilling rates were found to be independent of flowrate for the same total amount of infused water (i.e., 20% of animal live weight).

Water uptake by carcass sides during vascular infusion processing depended on temperature, flowrate, and infused water volume. However, water retention in carcass sides increased only marginally as medium flowrate was increased. Only the temperature and amount of infused water significantly affected water uptake by muscle tissues, as reflected in side weight gains. Sides from carcasses infused with water totalling 20% of the animal live weight gained about 4% more fluid than control sides subjected to conventional abattoir procedures. From tracer dye experiments, it appears that the bulk of water absorbed by the carcass was superficially retained. Such retained water could be readily removed by evaporation in a conventional chiller, resulting in negligible net carcass side weight change after 24 h.

An engineering model was developed to quantitatively assess the chilling efficiency

of vascular infusion. Vascular infusion of 1°C water totaling 10 and 20% of animal live weight removed 7.9 and 14.3% of the total energy released during chilling of beef sides down to 7°C, respectively. Time-temperature profiles of intact muscle predicted by the proposed mathematical model are in good agreement with experimental values.

Water with a temperature of 10°C exhibited lower resistance to flow through the vascular system than water at 1°C. A friction factor was used to estimate the pump pressure required to achieve uniform internal flow distribution throughout the intact carcass.

Flow patterns within the vascular system, as revealed by a limited number of tracer dye experiments, were characterized as plug flow with axial dispersion and dead space with either one vessel or two parallel vessels. Theoretical residence times were in good agreement with those obtained from experimental residence time distribution curves.

It was concluded that vascular infusion can be used to reduce or eliminate overall evaporative losses that occur in a conventional abattoir, and to accelerate the overall carcass chilling process.

ACKNOWLEDGMENT

I would like to express my gratitude to my supervisor, Dr. Roberto Segado, and to my co-supervisor, Dr. Steve Morgan-Jones, for their advice, guidance, support and encouragement throughout this project.

I would also like to thank Dr. L. Ozimek for serving as a committee member and for his valuable time in this project. My thanks are also due to Dr. J. Feddes for his participation as a member of the examining committee.

I wish to thank Mr. Doug McGinnis. His help and organization for this team work are sincerely appreciated.

The financial support provided by the Alberta Cattle Commission and the Alberta Government through its AARI matching grant program for major funding contributions is acknowledged.

I wish to thank Mr. Don Brereton and the Lacombe Research Station abattoir staff for their technical assistance during the infusion trials. Furthermore, I am very grateful to Mr. Brady Chabot for his help with instruments.

I wish to extend my thanks to all the friends and staff in the Department of Food Science and Nutrition for their moral support throughout my study.

Finally, I wish to express my deep appreciation to my husband, Shuo, for his patience and many sacrifices.

TABLE OF CONTENTS

CHAPTER

1. INTRODUCTION AND LITERATURE REVIEW 1

General Introduction 1
Objectives 7
Literature Review 8
Chilling Technology 8
Conventional Chilling 8
Rapid Chilling 12
Water Spray Chilling 14
Continuous vs. Batch Chilling Modes 15
Cold Shortening 18
Water Holding Capacity 19
Pre- and Post- mortem Infusion 22
Infusion of Enzymes 22
Infusion of Minerals 23
Infusion of Amino Acids, Sugars and Vitamins 24
General References 25

2. EFFECTS ON CHILLING EFFICIENCY AND WEIGHT CHANGE DURING VASCULAR INFUSION OF BEEF CARCASSES 36

Introduction 36
Materials and Methods 37
Results and Discussion 39
Effect of Total Amount of Infused Medium on Carcass Temperature 39
Effect of Infused Fluid Temperature on Chilling Rate 41
Effect of Flowrate on Carcass Temperature 42
Effect of Vascular Infusion on Weight Change of Beef Sides 43

Conclusions 44
References 54

3. MODELLING HEAT AND MASS TRANSFER CHARACTERISTICS DURING VASCULAR INFUSION OF BEEF CARCASSES 56

Introduction 56
Mathematical Model 58
Thermal Energy and Mass Balances 58
Heat Transfer Model 60
Momentum Energy Balance 61
Materials and Methods 62
Results and Discussion 63
Energy Removal by Vascular Infusion 63
Heat Transfer Model Predictions 65
Friction Loss in the Vascular System 65
Conclusions 67
References 77

4. RESIDENCE TIME DISTRIBUTION IN VASCULAR INFUSION OF BEEF CARCASSES 80

Introduction 80
Materials and Methods 81
Determination of Residence Time Distribution (RTD) 81
Calculation of Mean RTD from Experimental Data 83
Results and Discussion 84
Conclusions 85
References 94

5. GENERAL CONCLUSIONS AND RECOMMENDATIONS 95

LIST OF TABLES

Table

2.1. Effect of total volume of infused 1°C water on carcass temperature 45 minutes after slaughter 45

2.2. Effect of infused medium temperature on carcass temperature 45 minutes after slaughter 46

2.3. Effect of infusion flowrate on carcass temperature 45 minutes after slaughter 47

2.4. Carcass weight loss in the chiller 48

3.1. Rate of carcass weight change during infusion at different flowrates 68

3.2. Mass fractions and specific heats of different carcass side components 69

3.3. Carcass temperatures and fraction of heat removed during vascular infusion 70

3.4. Overall heat transfer parameter (UA) for different flowrates 71

3.5. Experimental friction factors of the vascular system 72

4.1. Calculation of residence time distribution from experimental data for 190 kg animal at flowrate of 7.6 l/min 86

4.2. Calculation of residence time distribution from experimental data for 290 kg animal at flowrate of 10.0 l/min 87

4.3. Calculation of residence time distribution from experimental data for 520 kg animal at flowrate of 11.5 l/min 88

LIST OF FIGURES

Figure

2.1. Schematic of experimental arrangement showing fully intact beef carcass and vascular infusion apparatus and instrumentation 49

2.2. Time-temperature profiles in muscle processed with and without vascular infusion 50

2.3. Time-temperature profiles in muscle processed by vascular infusion using water at 1°C and 10°C 51

2.4. Time-temperature profiles in muscle processed by vascular infusion using 10°C water at three flowrates 52

2.5. Carcass yield for different combinations of infusion parameters 53

3.1. Schematic of experimental arrangement showing fully intact beef carcass and vascular infusion apparatus and instrumentation 73

3.2. Variation of carcass weight during vascular infusion at different flowrates 74

3.3. Flow model for vascular infusion of beef carcasses 75

3.4. Water pressure versus time profiles at pump outlet (P1) and catheter tip (P2) 76

4.1. Residence time distribution for 190 kg animal at flowrate of 7.6 l/min 89

4.2. Residence time distribution for 290 kg animal at flowrate of 10.0 l/min 90

4.3. Residence time distribution for 520 kg animal at flowrate of 11.5 l/min 91

4.4 Single-vessel plug flow model 92

4.5 Parallel-vessel plug flow model 93

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

GENERAL INTRODUCTION

Dressed carcasses are chilled in a conventional abattoir from temperatures of about 40°C down to 7°C prior to shipping or carcass fabrication. The purpose of chilling is to prevent bacterial growth on the newly exposed meat surface, thus prolonging the product shelf life.

Nottingham (1982) presented an extensive review on the microbiology of meats and rational for effective microbiological controls in an abattoir. It is generally agreed that the undisturbed interior of healthy intact muscle is microbiologically sterile (Shaw *et al.*, 1986 and Gill, 1979). The surface of carcasses, however, can be easily contaminated by skinning, eviscerating and dressing procedures within the abattoir. Fortunately, the risk of initial post slaughter contamination at high interior muscle temperature can be considerably reduced by means of chilling.

Chilling of beef carcasses in a conventional batch chiller consumes a considerable amount of energy, which is estimated at 35% of the total energy used in a meat processing facility (Collett and Gigiel, 1986). Likewise, moisture loss from beef carcasses during chilling strongly affects profitability in the meat industry. Demands for advanced chilling technologies toward improved meat quality have increased as a result of the

implementation of European Economic Community (EEC) temperature regulations along with economic requirements to maximize throughput and minimize the processing costs associated with energy consumption and moisture loss from carcass sides. Recently, increasing attention has been paid to the importance of early postmortem chilling rate on meat marketability in terms of drip potential, appearance and eating quality, particularly texture. Likewise, the cost of moisture losses during chilling are higher than the most optimistic energy savings. This has encouraged researchers to explore new technologies aimed at minimizing carcass weight losses during chilling.

Conventional chilling modes involve use of air to remove thermal energy from the carcass and transfer it to the evaporation coils and refrigerant of a refrigeration system. Chillers can be sized to accommodate virtually any industrial thermal load, yet the overall chilling rate is generally limited by the rate of heat transfer across the carcass surface. This rate depends on the temperature difference between air and carcass surface, carcass surface/volume ratio, and "Biot number", which indicates the importance of boundary-layer heat transfer relative to internal heat conduction. Several approaches can be adopted to increase the cooling rate: increasing the temperature difference, increasing the meat surface area relative to its volume and reducing the thickness of the thermal boundary layer.

Throughput is very important for the meat industry since longer chilling times result in large inventories of beef being held in expensive, large chilling facilities and increased operating costs. Ideally, the meat industry prefers a 24 h cycle whereby meat can be shipped out the day after slaughter. EEC temperature regulations require a maximum internal muscle temperature of 7^{o}C prior to shipping or fabrication (Council of the European Communities, 1964). However, James and Bailey (1989) and Wotton (1986) found that for conventional single stage chilling regimes, only relatively light and

lean beef sides (< 105 kg) will reach the required 7°C in deep leg tissue within 24 h . This means that a conventional batch chilling system may require as much as 36-48h to achieve an interior muscle temperature of 7°C. Furthermore, after investigating energy usage and weight loss in five batch commercial beef chillers, Collett and Gigiel (1986) noted that evaporative weight losses in batch mode could be as high as 1.8 to 3.5% of dressed carcass weight. Unsatisfactory performance of batch chilling systems has motivated the meat industry to consider using rapid chilling as an alternative method.

Rapid chilling systems using high velocity air at sub-zero temperatures of -15 to -70°C are now seen as a viable means to reduce cooling time, thus increasing throughput and minimizing shrinkage and drip loss. It is also demonstrated that rapid chilling of carcass surfaces results in improved hygienic conditions and longer product shelf life. Bendall (1972) noted that a reduction of meat tissue temperatures to 10°C or lower prior to pH decline to 6.2 may cause cold shortening, which is linked to toughening. However, cold shortening can be prevented by application of electrical stimulation during the early post-mortem period (Locker, 1985). It was found that beef subjected to electrical stimulation before rapid chilling has similar to or better quality than conventionally chilled carcasses (Aalhus *et al.*, 1991).

Rapid chilling may cause undesirable surface freezing, which produces increased drip loss on final cutting (Gigiel *et al.*, 1985). Rapid chilling also results in non-uniform internal temperature distribution and poor energy efficiency when constant sub-zero air temperatures are maintain throughout the entire chilling process. Since almost two-thirds of the total sensible heat is removed during the first few hours of chilling (Joseph and McKenna, 1987), a relatively brief rapid chilling stage followed by a temperature equilibration stage under conventional chilling conditions can be used to offset those undesirable effects (Bowater, 1987).

Increased chilling rates can also be achieved by hot processing, which involves breaking down prerigor carcasses into primal cuts and/or separating muscle from bone, extra fat and connective tissue prior to chilling. The reduced thickness and increased surface/volume ratio of individual cuts results in increased chilling rates. There is considerable potential for energy savings and other attractive advantages in terms of chilling rate, reduced cooler space and distribution costs associated with hot processing (Henrickson and Asghar, 1985). McGinnis *et al.* (1993) found that the energy savings achieved by modified hot processing were between 18 and 52% of that currently used to chill beef sides. However, because excised prerigor muscle is more susceptible to rigor shortening, because the increased surface area exposes the hot wet meat to a greater number of microorganisms and results in a very high rate of evaporative weight loss unless wrapped (James, 1987), and because the smaller pieces impose an added handling problem under the present processing practices at existing meat plants, hot processing has not been adopted by industry and much of the research in this area has focused on providing a better understanding of post-mortem muscle biochemistry (Cuthbertson, 1980; Henrickson and Asghar, 1985 and Taylor *et al.*, 1981). According to James (1987), breaking the carcass down to primal cuts does not improve heat transfer rate when the cuts are packaged in standard cardboard boxes prior to chilling due to poor heat conductivity of the package.

Although increasing air velocity reduces the thermal boundary layer thickness, this has little effect on the overall chilling rate, since heat transfer is strongly limited by internal resistance. As the power consumption of fans required to move air over the carcass increases with the cube of the velocity, there is little to be gained by using velocities greater than about 2 m/s (Kerens, 1976).

In recent years, water spray chilling has gained acceptance by the beef industry as a means to reduce carcass moisture loss. These systems use a combination of air and water sprays during the initial chilling period followed by air only for the rest of the chilling cycle. Jones and Robertson (1988) and Allen *et al.* (1987) showed that spray-chilling reduced carcass shrinkage by about 1% compared with conventional means.

Vascular infusion of pre-chilled water or solutions into intact beef carcasses immediately after slaughter has the potential advantage of increasing early post-mortem chilling rates and minimizing weight losses from beef sides over conventional chilling. Flushing the vascular system with cold water can provide an effective chilling method since the surface area of the vascular system is significantly greater than the exterior surface of a carcass. Also, there is a shorter distance between heat source (muscle tissue) and heat sink (vein, artery, etc.) compared to chilling of carcass sides in conventional chillers.

It is known that live beef animals loose weight prior to slaughter (Jones *et al.*, 1988; 1990; Schaefer *et al.*, 1990; 1992). Making cattle drink water before slaughter could be used to reduce weight losses, but there is no guarantee all animals will drink. The introduction of fluid through the vascular system immediately after slaughter could also achieve the purpose of weight recovery. Furthermore, the high muscle pH following slaughter promotes a high water holding capacity, which offers a better opportunity to increase carcass yield.

There are many studies on immediate pre- or post-mortem infusion of proteolytic enzymes, minerals, amino acids, sugars or vitamins to improve meat tenderness, flavor and appearance (Bradley *et al.*, 1987; Koohamaraie *et al.*, 1988; Asghar *et al.*, 1989 and Cunningham and Francis, 1981). Therefore, besides water, various solutions could be

used as the flushing medium to improve muscle quality while achieving the desired chilling effect. For instance, vascular infusion of glucose solution may affect the rate of post-mortem metabolism and muscle flavor development; the infusion of lactate may result in an earlier onset of rigor mortis and prevent cold toughening; and infusion of vitamin E, an effective anti-oxidant, may prevent rancidity and improve muscle color. As a result, vascular infusion has the potential not only to improve carcass yields but also to modify post-mortem rigor processes and even to influence the storage properties of muscle.

OBJECTIVES

The general objective of this study was to evaluate and characterize heat and mass transfer during vascular infusion of beef carcasses with pre-chilled water, and to formulate appropriate mathematical models that can be used in designing commercial vascular infusion processes.

Particular objectives were:

1) to determine the effects of fluid temperature, flowrate and total volume of infused water on rates of temperature decline in beef carcass muscles during vascular infusion and subsequent chilling in a conventional chiller.
2) to investigate the effects of vascular infusion on changes in carcass moisture content during postmortem processing and chilling.
3) to determine the amount of thermal energy removed by vascular infusion.
4) to develop a mathematical model capable of predicting time-temperature profiles of intact muscle during chilling by vascular infusion.
5) to assess the effectiveness of vascular infusion in improving chilling efficiency.
6) to investigate the effect of pump discharge pressure on the behavior of water circulation and temperature distribution throughout entire carcasses.

LITERATURE REVIEW

Chilling Technology

Conventional Chilling

In conventional chilling, carcasses are chilled at cooler temperature close to 1°C. Considerable research has been undertaken to determine the influence of chilling conditions and carcass variables on chilling rate and weight loss (James and Bailey, 1989; 1986; Gigiel *et al.*, 1989; Collett and Gigiel, 1986; Wotton, 1986; Kerens, 1976; Lovett, 1976; Radford, 1976; Bailey, 1972; and Levy, 1972). Relevant factors affecting chilling include air temperature, velocity and relative humidity, as well as carcass weight and fat content. Adequate knowledge of the effect of these parameters on chilling rate and moisture loss is required for the proper design and optimal operation of conventional chillers to produce high quality meat.

Factors Affecting Chilling Rate: James and Bailey (1989) recently published a comprehensive review article on conventional batch chilling of beef. They showed that increasing air temperature from 0 to 4°C results in a 36% increase in the chilling time required to reach 7°C in the deep leg muscle of a 100 kg side (20.3 vs. 27.7 h, respectively) with air velocity equal to 3 m/s, and a 49% increase for a 220 kg side at air velocity of 0.5 m/s. Inability to vary operating conditions in batch chilling systems makes it impossible to provide satisfactory chilling rates throughout the entire cycle, since beef carcasses release most of their heat during the initial hours of chilling; i.e. the initial chilling rate is much higher than the average rate of heat removal for the entire process (James, 1987). Air temperature rise in the chiller during peak load hours leads to

extended chilling cycles. Although using a chilling room with oversized refrigeration capacity may solve this problem, this would result in poor energy inefficiency.

Increasing the air velocity produces a substantial reduction in chilling time at low air velocities, while increasing air velocity beyond 2 m/s has no significant effect on chilling rate (Kerens and Visser, 1978 and Bailey and Cox, 1976). Power consumption by the fans increases with the cube of the air velocity. As shown by James and Bailey (1989), increasing air velocity from 0.5 to 2 m/s resulted in 4 to 7 h shorter chilling time for a 140 kg side weight, but it imposed a six-fold increase in fan power. Air velocities greater than 3 m/s consume an excessive amount of energy and may increase moisture loss from carcass sides, while resulting in little reduction of chilling times.

Kerens and Visser (1978) showed that decreased relative humidity resulted in slight reduction in chilling time, apparently due to increased evaporative cooling of carcass surfaces. This is generally inadvisable unless water was added to the carcasses because increased chilling rates would result in larger weight losses, which are more costly than any savings resulting from reduced chilling times.

Carcass side weight has a remarkable effect on chilling rates. The chilling time required to reach a deep leg temperature of 7^{o}C at air temperature of 0^{o}C and velocity of 1 m/s was from 25.6 h for a 100 kg side and 42.1 h for a 220 kg side — a 64.5% increase (Gigiel and Peck, 1984). The effect of fat content of sides on the chilling rate can not be established very precisely since fat content and animal weight are not independent. Nevertheless, fat animals exhibit slower chilling rates than lean animals due to the insulating function of the fat layer. A comparison could only be made over a limited weight range. Thus, Bailey and Cox (1976) indicated that for 140 kg sides in air at 0^{o}C,

0.5 m/s, chilling times of the fattest carcasses could be as high as 20% above average and as low as 20% below average for the leanest carcasses.

Factors Affecting Weight Loss: The importance of air conditions on weight loss was discussed by Kerens (1976). Through extensive study on evaporative weight loss from beef carcasses, Kerens found that a constant air temperature of 4°C produced the highest weight loss during chilling. Kerens also found that 55% of the moisture loss occurred in the first two hours of chilling. This results from high water activity of wet carcass surfaces and high muscle temperature during the initial chilling period. It also points out the importance of controlling the rates of heat and mass transfer in the early stages of chilling.

Although air velocity has almost the same effect as air temperature on the weight loss, as shown by James and Bailey (1989), Bailey (1974) and Kerens (1976) found only marginal changes in moisture loss when increasing air velocity from 0.5 to 1 m/s. Gigiel and Peck (1984) pointed out that there were considerable economic advantages to be gained in systems where the air speed was reduced after most of the heat has been removed from the carcass, since internal heat conductivity is no doubt the rate-controlling step. Variable air speed can be used to improve the economics of refrigeration systems. Malton and James (1984) suggested that the lowest feasible air temperature, highest relative humidity and minimum air velocity needed to achieve uniform air temperature within the chiller be used to minimize weight loss.

Relative humidity of air has a stronger effect on weight loss than air temperature or air velocity. According to James and Bailey (1989), reducing relative humidity from 95 to 80% increased carcass weight loss by nearly 0.5% over an 18 h chilling cycle with air at 0°C .

As carcass side weight increased from 50 kg to 170 kg, the evaporative loss after a 18h chilling period at 0°C, 0.75 m/s and 95% relative humidity decreased by up to 1% (James and Bailey, 1989). As well, according to Joseph and McKenna (1987) weigh loss for lean sides with little or no fat cover could be up to 1% higher than sides of similar weight with a thick covering of fat. This result is quite important given the increasing demand for lean carcasses in the meat industry. Thus, reduction of the weight loss from lean sides could result in significant economic benefits.

As required by EEC temperature regulation, carcass beef should not be shipped after slaughter until its temperature has been reduced to a maximum of 7°C throughout the carcass (Council of European Communities, 1964). Based on a study of energy usage and weight loss in five commercial beef chillers, Collett and Gigiel (1986) found that as much as 48 h may be required to reach the target temperature of 7°C in the deep muscle (i.e., at the thermal center of a beef side). Moreover, a recent study (Gill *et al.*, 1991) showed that 85% of the carcasses exiting the chiller in a modern beef plant had deep hind limb temperatures in excess of 10°C after a 24 h chilling cycle. High deep muscle temperature in cuts from post-fabrication of carcasses may lead to reduced meat storage life, since most box storage facilities are designed to maintain temperature rather than chill product.

In addition, conventional chilling results in considerable temperature variation among the specified muscle groups. For instance, the time required to reach 7°C between loin muscle and deep round muscle can differ by as much as 10 h. Thus, conventional chilling may not meet the target temperature of 7°C in deep round muscle within 24 hours but it may chill the loin muscle to 7°C in less than 10 hours. It has been known for over 30 years that pre-rigor muscle with pH > 6.2 chilled below 10°C causes cold-shortening which results in tough meat (Locker and Hagyard, 1963). As a result, Bendall (1972)

recommended that carcasses should not be chilled below 10°C within 10 hours after slaughter in order to avoid cold shortening. Based on this criterion, Kerens (1976) found that cold shortening was possibly a problem in loin muscle under conventional chilling conditions, specially for lean carcasses with little fat cover (< 7 mm fat).

Due to relatively slow cooling rates during the initial stage of conventional chilling, there is a high rate of evaporative moisture loss from the carcass surface. As reported by Collett and Gigiel (1986), evaporative moisture losses from carcass sides during conventional chilling account for 1.8 to 3.5% of dressed carcass weight. Even in a well-run conventional chiller, moisture loss may be as high as 1.1 to 2% (Gigiel, 1985).

Conventional chilling can not meet meat industry requirements of high post-mortem chilling rate, even temperature distribution, and low evaporative moisture loss. In reality, the meat industry prefers a 24 h chilling cycle, since the longer it takes to chill beef carcasses to 7°C the more refrigeration space and working capital are required. As well, reduction of weight losses is even more critical for the profitability of the meat industry than energy consumption.

Rapid Chilling

Rapid chilling involves use of very low, sub-zero temperatures (e.g., -5 to -70°C) and high air velocities to chill the carcasses. Major advantages of rapid chilling are significant reductions in cooling time, shrinkage and drip loss. Watt and Herring (1974) chilled beef carcass sides with air at temperatures of -29 and -45.5°C and a constant velocity of 3 m/s for various periods of time; this reduced rib temperatures to 10°C within 4-6 h of chilling. Their research demonstrated that rapid or cryogenic chilling reduced 24h shrinkage by 0.09 to 0.67% of side weight over that produced by conventional chilling (air

at 2-3°C and 1 m/s). Bowater (1986) also found that 5 h rapid chilling with air at -15°C and 2 m/s reduced evaporative moisture loss by 50% (relative) over 24 h conventional chilling and by 76% (relative) over 48 h conventional chilling. With the trend toward leaner cattle in the Canadian marketplace, using rapid chilling to minimize evaporative moisture loss is probably the most promising way to improve the process economics, since moisture loss from leaner carcass sides is a major problem affecting the profitability of meat plants.

On the other hand, introduction of rapid chilling, in which the interior of muscle reaches 10°C less than 10 hours post-mortem, may affect meat tenderness. Because of the risks of cold shortening in beef muscle, there have been few studies which have attempted to examine the effects of rapid chilling on beef quality. Watt and Herring (1974) indicated that loin muscles from sides subjected to rapid chilling were 9-16% tougher compared to conventional chilling. However, Bowling *et al.* (1987) noted that sides chilled at -70°C for 5 h and subsequently held at 16°C for 4 h and 1°C for 15 h had higher taste panel tenderness and shear force scores than those conventionally chilled at -7°C for 24 h. A possible explanation is that the equilibration period at 16°C for 5 h resulted in some reversal of cold shortening. Woltersdorf (1988) reported that chilling at -10°C for 3 h produced toughening in the sirloin and outside round muscle compared to conventional chilled sides.

Adoption of electrical stimulation during the early post-mortem period is known to prevent cold shortening. Thus, rapid chilling can be employed in conjunction with electrical stimulation to produce tender meat. A series of experiments have been carried out by Aalhus *et al.* (1991) to examine the effects of rapid chilling (-20°C, 3 h) followed by conventional chilling, with and without electrical stimulation, on carcass weight loss, pH and temperature decline, and meat quality. For both the *longissimus dorsi* (LD) and

semimembranosus (SM) muscle, the most rapid decline of pH occurred in carcasses subjected to rapid chilling with electrical stimulation, and the least rapid decline of pH was in carcasses subjected to rapid chilling without electrical stimulation. As compared to conventionally chilled carcasses, rapid chilling without electrical stimulation resulted in slightly darker meat at the time of grading and tougher meat after 6 days of aging. Application of electrical stimulation prior to rapid chilling can produce as good or better meat quality than conventional chilling.

Water Spray Chilling

Although there is considerable interest in methods of reducing chilling time and evaporative loss, all accelerated cooling systems are likely to be more expensive to install and operate than conventional plants. Therefore, to be attractive enough, any new accelerated chilling system must offer substantial savings in terms of increased throughput and/or higher yields of marketable meat. New techniques which can reduce chilling costs with little modification to existing facilities are more likely to be accepted by industry. Spray chilling is one such example which is rapidly gaining commercial acceptance for beef (Allen *et al.*, 1987; Jones and Robertson, 1989; Heitter, 1975 and Packerland, 1985). Practical spray chilling systems use a combination of air and water sprays during the initial chilling period and then air only for the rest of the chilling cycle. The sprays are not applied continuously but in short bursts, 90 s at 15 min. intervals for the first 8 h (Allen *et al.*, 1987), 60 s at 15 min. interval for the first 4 h (Jones and Robertson, 1989) or 30 s at 30 min. intervals for the first 12 h (Hamby *et al.*, 1987) in the chilling system.

According to Allen *et al.* (1987), carcass shrinkage was reduced from 1.46 to 0.32% when unshrouded carcasses were sprayed chilled with cooled water at 3°C for 8 h

(90 s duration every 15 min.). Jones and Robertson (1988) found that shrouded lean carcasses (7 mm fat) had lower shrinkage than unshrouded fat carcasses (13 mm fat) after 8h of spray-chilling. Subsequently, Jones and Robertson (1989) demonstrated that spray-chilling could substantially reduce carcass shrinkage, particularly during the initial 24 h period. Also, they found that the longer the spray-chilling period, the greater the potential savings in shrinkage; however, spray-chilling periods as long as 12 h had no effect on meat color, drip loss or muscle shear value. A recent study (Greer and Jones, 1993) investigated the effect of water spray-chilling on beef carcass quality, bacteriology and retail shelf life in a research abattoir. They found that there were no detrimental effects on anaerobic bacterial growth on spray-chilled beef carcasses during vacuum storage, or aerobic bacterial growth on steaks from spray-chilled beef carcasses during retail display. These results may stimulate the meat industry to start or continue using spray-chilling to reduce carcass shrinkage without compromising quality or increasing spoilage losses.

Continuous vs. Batch Chilling Modes

Batch chilling systems have been dominant in the beef industry for years. In a batch chiller, the temperature is generally fixed for the entire cooling period. The required chilling time is determined by the temperature of the slowest-cooling meat component (e.g., deep hip) and, in many cases, by the requirement of preventing cold shortening in important muscle groups, such as *longissimus dorsi* in beef (Locker, 1960; 1985 and Marsh *et al.*, 1974). In a medium size chiller, there are six to eight lines, each containing 15 to 20 suspended carcasses. The rails are about 1.0-1.2 m apart. Carcass spacing along the rail is usually in the range 0.75-0.9 m. Typically, air is blown over the beef carcasses by a row of fans along one or both sides of the chiller.

Besides their unsatisfactory chilling rates, batch chillers have the added disadvantage of inefficient energy and labor use as well as unchangeable chiller conditions. According to Joseph and McKenna (1987), the inefficient energy use in batch systems is partly due to the operation of chilling rooms containing fewer carcasses than their design capacity. Since batch chillers are generally run at the same rate regardless of load, energy consumption per carcass in a partially full batch chiller is higher than in a full chiller. Also, refrigeration systems are normally designed to handle the maximum rate of heat removal from carcasses, although cooling requirements after 4 to 10 hours fall to about one-third of the maximum heat load (Joseph and McKenna, 1987).

Fan operation is another source of energy waste. Closely packed carcass sides in the chiller reduce air flow over individual carcass surfaces and increase pressure drop. As a result, increased power is required by the fans to maintain adequate chilling rates. Power consumption of fans increases with the cube of volumetric flow rate. Maintaining a constant fan speed throughout the entire cycle is a waste of power, since the rate of heat removal from carcasses decreases with time and is independent of air velocity during much of the chilling cycle.

Another disadvantage of batch systems is that because of non-uniform air distribution, chilling rates of individual carcasses depend on their location within the chiller (Wotton, 1986 and Joseph and McKenna, 1987). Carcass sides located closer to fans are subjected to higher air velocities and lower temperatures than those further away from the fans. Distance between rails or between sides will also affect carcass chilling rate and meat quality.

Finally, batch chillers are not well suited to the continuous production mode of abattoirs, which can negatively impact on overall plant efficiency. Inefficient use of labor

to move carcasses manually from slaughter hall to chill is also quite common in batch-mode operations.

Greater control of carcass chilling using energy efficient continuous chilling tunnels has gained much attention. Particularly, environmental conditions in continuous chilling tunnels are optimized at each of several chilling stages. Continuous multistage chilling systems can be developed with a specific rationale, based on a number of production considerations, such as labor, energy consumption and process time. This concept has been successfully applied in hog processing plants, where early postmortem rapid chilling with sub-zero air is becoming the norm. Given the economical benefits of continuous chilling tunnels, Joseph and McKenna (1987) suggested replacing batch chilling by line or continuous chillers in which beef sides move slowly through a long serpentine tunnel and are subject to a multi-zone chilling regime. In each particular chilling regime, air speed and temperature can be precisely controlled. Meanwhile, the number of chilling zones or stages and length of time spent in each would be adjusted according to carcass size, shape and composition, so as to optimize both energy consumption and quality. Extensive research on line chilling of beef sides has been published by Drumm and McKenna (1992a, b), Drumm *et al.* (1989) and Joseph and McKenna (1987) to investigate the feasibility of replacing current batch chilling process. Drumm and McKenna (1992a) also developed a computer program to predict meat temperature in continuous systems. Effects of continuous or line chilling with many different combinations of chilling zones on temperature, weight loss and cold shortening were discussed by Drumm and McKenna (1992b). They indicated that orientation of sides with respect to the fans played an important role on chilling rate and carcass weight loss. Although continuous chilling requires a higher capital investment than batch equipment, the added cost will be offset by

the advantages of better control, near-optimal chilling conditions and lower energy and labor costs.

Cold Shortening

Cold-shortening phenomenon associated with toughening of cooked meat was first discovered by Locker and Hagyard (1963). The strong, irreversible contraction of the muscle is induced by a reduction of muscle temperature below 10°C before muscle pH had fallen below 6.2 and adenosine triphosphate (ATP) reserves had been reduced below 50% of the initial postmortem level (Davey and Gilbert, 1974; Locher, 1985 and Bendall, 1972). This possibly results from inhibition of the Ca^{++} sequestering performance of the triads of the sarcoplasmic reticulum (SR). The release of Ca^{++} ions into the muscle fibre cytoplasm, where it appears to stimulate the dephosphorylation of ATP by myosin ATPase, enables the binding of the actin-myosin contractile filaments (Pearson, 1987).

Marsh and Leet (1966) illustrated the effect of varying degree of cold-shortening on the toughness of cooked beef and lamb muscle. Interestingly, maximum toughness in beef muscle occurs when shortened to 60% of slack length; further shortening down to 40% slack length reverses the toughing processing. Bendall (1972) proposed that reversible toughening could be caused by the microstructure of muscle fibres being damaged by the unphysiological degree of shortening in such a way as to destroy their longitudinal cohesion.

Locker and Hagyard (1963) showed that muscle shortening ranged from a minimum of 10% when muscles were allowed to reach rigor at temperatures between 15 and 20°C to a maximum of 50% at 0°C. As a result, considerable research has focused on carcass conditioning at warm temperatures for a certain period of time in order to

improve meat tenderness (Smith *et al.*, 1970; 1971; Bouton *et al.*, 1973a; b). Interestingly, muscle going into rigor at warm temperatures (43°C) also exhibits shortening, though less severe than that at 0°C (30% vs. 50%). Cold shortening begins immediately with chilling and is most rapid in the first 1-2 hr. Lochner *et al.* (1980) found that carcasses subjected to different chilling treatments had almost the same sarcomere length but significantly different tenderness. They also showed that tenderness was highly dependent on the muscle temperature attained at 2 hour post-mortem (27-40°C), and delayed chilling during the first 2-4 hour postmortem could improve the tenderness of slowly chilled beef sides. Thus, the significance of cold shortening on tenderness, as measured by shear force, may depend upon sarcomere shortening as well as upon the strength of bonds formed between myosin heads and actin-tropomysin-tropinin complex. This is consistent with earlier reports by Smith *et al.* (1971) and Bouton *et al.* (1973), who found no difference in sarcomere length between 0 and 16°C even though the shear force at 0°C was much greater than that at 16°C. These authors attributed their findings to the early action of proteolytic enzymes.

Water Holding Capacity

Water represents approximately 75% of the weight of freshly excised muscle. The content and distribution of water in meat can strongly affect its firmness, toughness, softness, juiciness and appearance (Kauffman and Marsh, 1987 and Offer and Knight, 1988).

The ability of meat to immobilize or bind water is of great importance for the quality of meat and meat products. As well, undesirable weight loss during storage, freezing and thawing, or cooking of meat is related to water binding by muscle (Hamm,

1986). Therefore, investigation of the water holding capacity is of considerable economic interest.

Water holding capacity in the muscle is defined as the ability of meat to hold its own or added water during application of force. Changes in water holding capacity are a very sensitive indicator of changes in the charge and structure of myofibrillar proteins (Hamm, 1960; 1975). Water in meat is predominantly retained in the myofibrillar framework. The volume of myofibrils is critically important to water holding capacity.

Muscle temperatures strongly influence postmortem rates of glycolysis, glycogenolysis, ATP turnover and enzyme activity, and consequently affect the rates and extent of rigor mortis, cold contracture and pH fall in muscle. It appears that all of these changes affect the water holding capacity of meat. Changes in water holding capacity occurring during storage depend on the extent to which bulk phase water is immobilized within the microstructure of the intact tissue (Hamm, 1975). The loss of water holding capacity is visible in the form of drip loss, which refers to the slow formation of red coloured exudate from meat without application of external forces (Hamm, 1986). Drip takes place mainly after rigor mortis and cutting. It contains myoglobin and a number of uncharacterized sarcoplasmic proteins. In the process of drip, unbound fluid is transported to cut ends of the meat along extracellular passages adjacent to the endomysium and connective tissues surrounding the muscle bundles. The amount of drip can vary from 0.1% to 10% of the lean meat weight (Offer *et al.*, 1989). Drip losses depend on many factors including storage time, distance between cuts, cut orientation, number of cuts and temperature history of muscle.

The influence of pH on water holding capacity of muscle is related to interactions between proteins. The decline of pH in muscle tissue to near its isoelectric point is

thought to interfere with the water binding ability of polar groups on the muscle proteins. Water binding capacity exhibits a minimum at about pH 5.0 (Pedersen, 1987), corresponding to the isoelectric point of myosin or actin which make up the bulk of myofibrillar proteins. Above and below this pH, the myofilaments exhibit increased net charges; this results in increased interfilament spacing and loosened microstructure, thus increasing the water binding capacity. Wismer-Pedersen (1987) provided the relationship between the effect of pH on water binding capacity of meat and myofibrillar volume.

The effects of muscle temperature history and pH on water holding capacity discussed above are consistent with the common knowledge that pale-soft-exudative (PSE) meat can be prevented by rapid chilling (Honikel *et al.*, 1981 and Gigiel *et al.*, 1989). Also, Offer and Knight (1988) found that a decrease of postmortem temperature from 37 to 10^{o}C (experimental isothermal treatments) substantially reduced the subsequent amount of drip, although the reason for this is unclear.

Muscle shortening, whether by cold induction or by rigor mortis, appears to be responsible for a decreased water holding capacity by its effect on the volume of sarcoplasm. Wismer-Pedersen (1987) found that the combined effect of postmortem pH drop and rigor onset reduced the water content in myofibrils from 80% to 60% of total water in meat. He thought that two-thirds of this reduction resulted from the rigor bonds and the rest from the pH fall. The number of rigor bonds between myofilaments depended on the degree of contraction of the muscle fiber. Comparing water holding capacity of 15% contracted meat with 40% contracted meat, the more contracted meat had significantly lower water binding capacity (Wismer-Pedersen, 1987).

Pre- and Post-mortem Infusion

Meat quality may be defined by the consumer in terms of tenderness, flavor, leanness, juiciness and colour. Many studies have been conducted on pre- or post-mortem infusion of substances such as enzymes, minerals, sugars and amino acids to improve meat eating characteristics since the early 1960's.

Infusion of Enzymes

Tenderness is generally regarded as one of the most important quality attributes of meat. Tenderness can be influenced by handling procedures immediately before, during and after slaughter. Proteolytic enzymes have been used to reduce the effects of natural and abattoir factors inducing toughness. Since the 1960's, a series of studies have been conducted on the effects of injecting proteolytic enzymes into a live animal on tenderness. Goeser (1961), Robinson and Goeser (1962), Huffman *et al.* (1961, 1967a, b) and Smith *et al.* (1973) have shown antemortem injection of proteolytic enzymes increases the tenderness of cooked meat.

Proteolytic enzymes are derived from bacteria, fungi or plants. The best known and most commonly used is papain, a food grade enzyme, derived from the paw-paw (*Carica papaya*). Many years ago, Mexican Indians started to cook meat in paw-paw leaves in order to obtain tender meat. Papaya enzyme, marketed as ProTen, has been refined in oxidized form and patented by Beatrice Swift Ltd. (Bradley *et al.*, 1987). The enzyme in its inactive oxidized form is injected into the live animal via the jugular vein shortly before slaughter so that the circulatory system uniformly distributes the enzyme throughout the meat tissue. The enzyme becomes reactive by heating, since glycolysis

depletes muscle oxygen and reducing agents accumulate. Kim *et al.* (1981) reported that the optimum activity of papain occurred at 50°C. So far, no deleterious effects of papain have been reported. However, overtenderness of liver and kidney has been found by Huffman *et al.* (1967a), Lawrie (1979) and Thornton (1973). The commercial introduction of Swift's intravenous papain technique and the associated economic advantages due to increased beef tenderness are discussed by Pritchard (1971).

Infusion of Minerals

After Wierbicki *et al.* (1957) showed an improvement in beef tenderness by postmortem infusion of sodium chloride, the investigation of the tenderizing effects of antemortem infusion of sodium chloride at different concentration in cattle was carried out by Huffman *et al.* (1967a). Huffman found that the antemortem injection of a 0.9% sodium chloride solution resulted in improved steak tenderness, but saturated sodium chloride solution had no effect on tenderness. Cattle carcasses injected with saturated sodium chloride solution had darker colored meat than uninjected cattle. More recently, Koohmaraie *et al.* (1988) reported the acceleration of postmortem tenderization of ovine meat by postmortem infusion of 0.3 M $CaCl_2$. To avoid Ca^{++}-induced muscle shortening, low frequency electrical stimulation was used to diminish the ATP supply in the prerigor muscle prior to Ca^{++} infusion. Koohmaraie *et al.* (1988) suggested that postmortem infusion of carcasses with $CaCl_2$ solution along with low frequency stimulation would significantly reduce the aging time required to ensure meat tenderness.

Vavak *et al.* (1976) found the contents of three specific elements in muscle, Fe, Co and Zn, could be used as indicators to predict tenderness. As well, Seideman *et al.* (1989) found that concentrations of copper, iron and manganese in muscle could be positively

correlated to tenderness ratings. However, infusion of lamb carcasses with $ZnCl_2$ was found to inhibit post-mortem tenderization (Koohmaraie *et al.*, 1989).

Infusion of Amino Acids, Sugars and Vitamins

Identification of natural compounds, such as sugars and amino acids, contributing to beef flavor (Hsieh *et al.*, 1980) provided an alternative way to improve meat flavor through post-mortem infusion. Information on natural compounds responsible for meat flavor was provided by Batzer *et al.* (1960; 1962), Wasserman and Gray, (1965) and Zaika *et al.* (1968). Cunningham and Francis (1981) injected pineapple and barbecue flavored solution containing papain to turkeys. They found improved tenderness, juiciness, and flavor in the infused turkeys.

Other efforts have been directed at reducing lipid oxidation through the use of antioxidants. Buckley and Connolly (1980) reported that the rate of rancidity development in frozen pork could be reduced by adding vitamin E in the feed for seven days before slaughter of pigs. There is also ample experimental evidence on the protective role of α-tocopherol (vitamin E) against peroxidative reaction in cellular (Ingold *et al.*, 1987) and subcellular membranes (Asghar *et al.*, 1989a and Buckley *et al.*, 1989). Asghar *et al.* (1989a) and Buckley *et al.* (1989) demonstrated the beneficial effects of feeding vitamin E-supplemented diets to broilers and pigs, respectively, on the oxidative stability of membrane-bound lipids and meat quality. The advantages of feeding different levels of supplemental vitamin E on the quality of pork during refrigerated storage have been reported by Asghar *et al.* (1989b). Also, postmortem meat color of bulls can be improved by feeding the bulls with either glucose or electrolyte drinks immediately before slaughter (Schaeffer *et al.*, 1990; 1992).

GENERAL REFERENCES

Aalhus, J.L., Tong, A.K.W., Robertson, W.M. and Jones, S.D.M. 1991. The effect of rapid chilling on beef quality. Presented at the 37th International Congress of Meat Science and Technology, Set 1-6. Kulmbach, Germany.

Allen, D.M., Hunt, M.C., Luchiari Filho, A., Danler, R.J. and Goll, S.J. 1987. Effect of spray chilling and carcass spacing on beef carcass cooler shrink and grad factors. *J. Anim. Sci.* **64**: 165-170.

Asghar, A., Lin, C.F., Gray, J.I., Buckley, D.J., Booren, A.M., Crackel, R.L. and Flegal, C.J. 1989a. The influence of oxidised dietary oil and antioxidant supplementation on membrane-bound lipid stability in broiler meat. *British Poutry Science.* **30**: 815-823.

Asghar, A., Gray, J.I., Booren, A.M., Miller, E.R., Pearson, A.M., Ku, P.K. and Buckley, D.J. 1989b. Influence of dietary vitamine E on swine growth and meat quality. *Int. Cogr. Meat Sci. Technol.* **35**: 1065-1070.

Bailey, C. 1972. Factors affecting rate of cooling and evaporation. In *Meat Chilling-Why and How?* Cutting C. L. (Ed.). Meat Research Institute. Bristol, pp. 13.1-13.11.

Bailey, C. 1974. A re-examination of the factors affecting the chilling of beef carcasses. In *Abstracts and Communications of 20th European Meating of Meat Research Workers.* Dublin, Ireland, Sept., pp. 208-209.

Bailey,C. and Cox, R.P. 1976. *The chilling of beef carcasses.* The Institute of Refrigeration, London.

Batzer, O.F., Santoro, A.T., Landmann, W.A. and Schweigert, B.S. 1960. Precursors of beef flavor. *J. Agric. Food Chem.* **8**: 498-501.

Batzer, O.F., Santoro, A.T. and Landmann, W.A. 1962. Idetification of some beef falvor precursors. *J. Agric. Food Chem.* **10**: 94-96.

Bendall, J.R. 1972. The influence of rate of chilling in the develoment of rigor and 'cold shortenning'. In *Meat Chilling- Why and How?* Cutting C. L. (Ed.). Meat Research Institute. Bristol, pp. 3.1-3.6.

Bouton, P.E., Harris, P.V., Shorthose, W.R. and Baxter, R.I. 1973a. A comparison of effects of aging, conditioning and skeletal restraint on the tenderness of mutton. *J. Food Sci.* **38**: 932-934.

Bouton, P.E., Fisher, A.L., Harris, P.V. and Baxter, R.I. 1973b. A comparison of effects of some post-slaughter treatments on the tenderness of beef. *J. Food Technol.* **8**: 39-43.

Bowater, F.J. 1986. The economic of modern beef chilling systems. In *Recent Advancements and Develoments in the Refrigeration of Meat by Chilling*. Proceedings of the International Institute of Refrigeration, Commission C2: 165-171.

Bowling, R.A., Dutson, T.R., Smith, G.C. and Savell, J.W. 1987. Effects of cryogenic chilling on beef carcass grade, shrinkage and palatability characteristics. *Meat Sci.* **21**: 67-72.

Bradley, R., O'Toole, D.T., Wells, D.E., Anderson, P.H., Hartley, P., Berett, S. Morris, J.E., Tnsch, C.G. and Hayward, E.A. 1987. Clinical biochemistry and pathology of

mature beef cattle following antemortem intravenous administration of a commercial papain preparation. *Meat Sci.* **19**: 39-51.

Buckley, D. J. and Connolly, J.F. 1980. Influence of alpha-tocopherol (vitamine E) on the storage stability of raw pork and bacon. *J. Food Protect.* **43**: 265-267.

Buckley, D. J., Gray, J.I., Asghar, A., Price, J.F., Crackel, R.L., Booren, A.M., Pearson, A.M. and Miller, E.R. 1989. Effects of dietary antioxidants and oxidized oil on membranal lipid stability and pork product quality. *J. Food Sci.* **54**(5): 1193-1197.

Collett, P. and Gigiel, A.J. 1986. Energy usage and weight loss in beef and pork chilling. In *IIR Meat Chilling,* Bristol, II.R Paris. pp.171-177.

Council of the European Communities, 1964. Council Directive of 26 June, 1964 on health problems affecting intra-community trade in fresh meat, (64/433/EEC).

Cunningham, F.E. and Francis, C. 1981. Injectable-detectable: new process offer more tender poutry. *Feedstuffs* **53** (Sept.): 33.

Cuthbertson, A. 1980. Hot processing of meat: A review of the rationale and economic implications. In *Developments in Meat Science.* Applied Science Publishers, London. Vol. 1. pp. 61-88

Davey, C.L. and Gilbert, K. V. 1974. The mechanism of cold-induced shortening in beef muscle. *J. Food Technol.* **9**: 51-58.

Drumm, B.M., Joseph, R.L., and Mckenna, B.M. 1989. Line chilling of beef carcasses: the selection of cooling regimes and the prediction of performance. In *Food Properties and Computer-aided Engineering of Food Processing Systems.* Singh, R.P. and Medina, A.G.(Eds.) Kluwer Academic Publishers. Vol. **168**: 125-130.

Drumm, B.M., Joseph, R.L. and McKenna, B.M. 1992a. Line chilling of beef 1: The prediction of temperatures. *J. Food Engng.* **16**: 251-265.

Drumm, B.M., Joseph, R.L. and McKenna, B.M. 1992b. Line chilling of beef 2: The effect on the carcass temperature, weight loss and toughness. *J. Food Engng.* **15**: 285-312.

Gigiel, A.J., Collett, P. and James, S.J. 1989. Fast and slow beef chilling in a commercial chiller and the effect of operational factors on weight loss. *Int'l. J. Refrig.* **12** (November): 338-349.

Gill, C.O. 1979. Intrinsic bacteria in meat- a review. *J. Appl. Bact.* **47**: 367-378.

Goeser, P.A. 1961. Tendered meat through antemortem vascular injection of proteolytic enzymes. *Proc. Res. Conf. Am. Meat Inst. Found.* **13**: 55-58.

Hamby, P.L., Savell, J.W., Acuff, G.R., Vanderzant, C. and Cross, H.R. 1987. Spraying-chilling and carcass decontamination system using lactic and acetic acid. *Meat Sci.* **21**:1-14.

Hamm, R. 1960, Biochemistry of meat hydration. *Adv. Food Res.* **10**: 355-443

Hamm, R. 1975. Dehydration of meat. In *Meat*. Cole, D.J.A. and Lawrie, R.A. (Eds.). Butterworth, London. pp.321-411.

Hamm, R. 1986. Functional properties of the myofibrillar system and their measurements. In *Muscle as Food*; Bechtel, P.J. (Ed.). Academic Press, Orlando, Florida. pp. 135-199.

Heitter, E.F. 1975. Chlor-chill. *Proc Meat Industry Res Conf.* AMIF. Arlington, VA, USA pp. 31-32.

Henrickson, R.L. and Asghar, A. 1985. Cold storage energy aspects of electrical stimulated hot-boned meat. In *Advances in Meat Research*; Pearson, A.M. and Dutson, T.R. (Eds.). AVI Publishing Co., Westport, Connecticut. pp. 237-268.

Honikel, K.O., Hamid, A., Fischer, C., and Hamm, R. 1981. Influence of postmortem changes in bovine muscle on the water-holding capacity of beef. Postmortem storage of muscle at various temperature between 0 and 30°C. *J. Food Sci.* **46**(1): 23-25.

Hsieh, Y.P.C., Pearson, A.M. and McGee, W.T. 1980. Development of a synthetic meat flavor mixture by using surface response methodology. *J. Food Sci.* **45**: 1125-1130.

Huffman, D.L., Palmer, A.Z., Carpenter, J.W. and Shirley, R.L. 1961. The effect of ante-mortem injection of papain on the tenderness of chickens. *Poul. Sci.* **40**: 1627-1630.

Huffman, D.L., Palmer, A.Z., Carpenter, J.W., Hentages, J.F. and Shirley, R.L. 1967a. Effect of ante-mortem injection of sodium chloride, papain and papain derivatives on the tenderness of beef cattles. *J. Animal Sci.* **26**: 285-289.

Huffman, D.L., Palmer, A.Z., Carpenter, J.W., Hargrove, D.D. and Koger, M. 1967b. Effect of breeding, level of feeding and antemortem injection of papain on the tenderness of weanling calves. *J. Animal Sci.* **26**: 290-293.

Ingold, K.U., Burton, G.W., Foster, D.O., Hughes, L., Lindsay, D.A. and Webb, A. 1987. Biokinetics of and discrimination betwwen dietary RRR- and SRR-α-tocopherol in the male rat. *Lipids* **22**: 163-172.

James, S.J. 1987. Effective systems for rapid cooling of carcasses and hot-boned meat. In *Accelerated Processing of Meat*. Romita, A. Valin, C. and Taylor, A.A. (Eds.) pp. 49-55.

James, S.J. and Bailey C. 1989. Process design data for beef chilling. *Int'l. J. Refrig.* **12** (Janunary): 42-49.

Jones, S.D.M. and Robertson, W.M. 1989. The effects of spray-chilling carcasses on the shrinkage and quality of beef. *Meat Sci.* **24**: 177-188.

Jones, S.D.M. and Robertson, W.M. 1988. The effects of shrouding on the appearances of spray-chilled beef carcasses. *Can. Food Sci. Technol. J.* **21**: 112-114.

Jones, S.D.M., Schaefer, A.L., Tong, A.K.W. and Vincent, B.C. 1988. The effects of fasting and transportation on beef cattle. 2. Body component changes, carcass composition and meat quality. *Livvest. Prod. Sci.* **20**: 25-35.

Jones, S.D.M., Schaefer, A.L., Robertson, W.M. and Vincent, B.C. 1990. The effect of withholding feed and water on carcass shrinkage and meat quality in beef cattle. *Meat Sci.* **28**: 131-139.

Joseph, R.L. and McKenna, B.M. 1987. In line chilling beef carcasses. In *Accelerated Processing of Meat*. Romita, A. Valin, C. and Taylor, A.A. (Eds). pp.57-68.

Kastner, C.L. 1981. Livestoke and meat: Carcasses, primals and subprimals. In *CRC Handbook of Transportation and Marketing in Agriculture*. Vol 1. Finney E.E. (Ed.). CRC Press Inc., Boca Raton. FL. pp. 239-258.

Kauffman, R.G. and Marsh, B.B. 1987. Quality characteristics of muscle food. In *The Science of Meat and Meat Products*; Price, J.F. and Schweigert, B.S. (Eds.). Food and Nutrition Press, Westport, Connecticut: pp. 349-369.

Kerens, G. 1976. The effect of environmental conditions on the chilling time and moisture losses of beef carcasses. In *Towards an Ideal Refrigerated Food Chain*; Melbourne, Australia. International Institute of Refrigeration. Paris, France. pp. 331-337.

Kerens, G. and Visser, C.J. 1978. Enviromental requirements during beef carcass chilling. CSIR Report ME 1728, Pretoria, SA.

Kerens,G., and Visser, C.J. 1978. Enviromental requirements during beef carcass chilling. CSIR Report ME 1597, Pretoria, SA.

Kim, K.S., Lee, S.Y. and Cheong, S.K. 1981. Research report of the office of rural development, Suweon, Korea, **23**: 75.

Koohmaraie, M., Babiker, A.S., Schroeder, A.L., Merkel, R.A. and Dutson, T.R. 1988. Acceleration of postmortem tenderization in ovine carcasses through activation of Ca^{++}-dependent proteases. *J. Food Sci.* **53**: 1638-1641.

Koohmaraie, M., Crouse, J.D. and Mersmann, H.J. 1989. Acceleration of postmortem tenderization in ovine carcasses through infusion of calcium chloride: Effect of concetration and ion strength. *J. Anim. Sci.* **67**: 934-942.

Lawrie, R.A. 1979. *Meat Science* (3rd), Pergamon Press, Oxford, 348.

Levy, F.L. 1972. Energy, time-temperature, and weight loss during meat cooling. In *Meat Chilling- Why and How?* Cutting C. L. (Ed.). Meat Research Institute. Bristol, pp.4.1-4.15.

Lochner, J.V.; Kauffman, R.G. and Marsh, B.B. 1980. Early-postmortem cooling rate and beef tenderness. *Meat Sci.* **4**: 227-241.

Locker, R.H. 1960. Degree of muscular contraction as a factor in tenderness of beef. *Food Res.* **25**: 304-307.

Locker, R.H. and Hagyard, C.J. 1963. A cold shortening effect in beef muscles. *J. Food Sci. Agric.* **14**: 787-791.

Locker, R.H. 1985. Cold induced toughness of meat. In *Advances in Meat Research*. Pearson, A.M. and Dutson, T.R. (Eds.). AVI Publishing Co., Westport, CT. pp. 1-44.

Lovett, D.A. 1976. Chilling of meat: Experimental investigation of weight loss. In *Towards an Ideal Refrigerated Food Chain*. Melbourne, Australia, International Institute of Refrigeration. Paris, France: pp. 307-314.

Malton, R. and James, S.J. 1984. Using refrigeration to reduce weight loss from meat. In *Profitability of Food Processing*. EFCE 26, Pergamon, London. pp. 207-217.

Marsh, B.B. 1972. Post-mortem shortening and meat tenderness. *Proc. Meat. Ind. Res. Conf.* Chicago. 109.

Marsh, B.B. 1974. Rigor mortis in beef. *J. Sci. Food Agric.* **5**: 70-75.

McGinnis, D.S. and Aalhus, J.L., Gariepy, C., Chabot, B., and S.D.M. Jones. 1993. A modified hot processing strategy for beef: Reduced electrical energy consumption in carcass chilling. Submitted to *Int'l J. Refrig.* for publication.

Nottingham, P.M. 1982. Microbiology of carcass meats. In *Meat Microbiology*. Brown, M.H.(Ed.). Applied Science Publishers Ltd., London, New York. pp.13-65.

Offer, G. and Knight, P. 1988. *Developments in Meat Science-4*, Lawrie, R. (Ed.). Elsevier Applied Science Publishers, New York. pp. 173-243.

Offer, G., Knight, P. Jeacocke, R., Almond, R., Cousins, T. Elsey, J., Parsons, N., Sharp, A., Starr, R. and Purslow, P. 1989. The structural basis of the water-holding appearance and toughness of meat and meat products. *Food Microstructure* **8**(1): 151-170.

Packerland, 1985. Quick chill carcass cooler. *Meat Industry*. October.

Pearson, A.M. 1987. Muscle function and postmortem changes, Chapter 4. In *The Science of Meat and Meat Products*; Price, J.F. and Schweigert, B.S (Eds.). Food and Nutrition Press Inc., Westpot, CT. pp. 155-192.

Pritchard, E.I. 1971. Pre-slaughter treatment in relation to nutritional quality of meat. *IFST Proceedings*, **4**: 118-123.

Radford, R.D. 1976. Water transport in meat. In *Towards an Ideal Refrigerated Food Chain*; Melbourne, Australia. International Institute of Refrigeration. Paris, France pp. 315-322.

Robinson, H.E. and Goeser, P.A. 1962. Enzymatic tenderization of meat. *J. Home Econ.* **54**:195-200.

Schaefer, A.L., Jones, S.D.M., Tong, A.K.W. and Young, B.A. 1990. Effects of transport and electrolyte supplementation on ion concentrations, carcass yield and quality in bulls. *Can. J. Anim. Sci.* **70**: 107-119.

Schaefer, A.L., Jones, S.D.M., Tong, A.K.W. Young, B.A., Murray, N.L. and Lepage, P. 1992. Effects of post-transport electrolyte supplementation on tissue electrolytes, hematology, urine osmolality and weight loss in beef bulls. *Livest. Prod. Sci.* **30**: 333-346.

Seideman, S.C., Cross, H.R. and Crouse, J. D. 1989. Variations in the sensory properties of beef as affected by sex condition, muscle and postmortem aging. *J. Food Qual.* **12**: 39-58.

Shaw, B.G., Mackey, B.M., and Roberts, T.A. 1986. Microbiological aspects of meat chilling. In *Recent Advances and Developments in the Refrigeration of Meat by Chilling*; Bristol. U.K., Sept. 10-12. International Institute of Refrigeration. Paris. pp. 25-30.

Smith, G.C., Arango, T.C. and Carpenter, Z.L. 1971. Effects of physical and mechnical treatments on the tenderness of beef logissimums. *J. Food. Sci.* **36**: 445-447.

Smith, G.C., Culp, G.R. and Carpenter, Z.L. 1970. Postmortem aging of beef carcasses. *J. Food Sci.* **43**: 823-826.

Smith, G.C., West, R.L., Rea, R.H. and Carpenter, Z.L. 1973. Increasing the tenderness of bullock beef by use of antemortem enzyme injection. *J. Food. Sci.* **38**: 182-183.

Smulders, F.J.M. and Johnson, J.L. 1990. Meat hygeine: processing, packaging, preservation. *Outlook on Agriculture* **19**(2):85-93.

Tayor, A.A., Shaw, B.G. and MacDougall, D.B. 1981. Hot deboned beef with and without electrical stimulation. *Meat Sci.* **5**: 109-123.

Thornton, H. 1973. *Aspects of Meat Inspection*. Bailliere Tindall, London, pp. 57.

Vavak, L. D., Satterlee, L. D. and Anderson, P.C. 1976. The relationship of cardiac shear and trace element content to beef muscle tenderness. *J. Food Sci.* **41**: 729-731.

Wasserman, A.E. and Gray, N. 1965. Meat flavor. 1. Fractionation of water-soluble flavor precursors of beef. *J. Food Sci.* **30**: 801-807.

Watt, D.B. and Herring, H.K. 1974. Rapid chilling of beef carcasses utilizing ammonia and cryogenic systems: effects on shrink and tenderness. *J. Anim. Sci.* **38**: 928-934.

Wierbicki, E., Cahill, V.R. and Deatherage, F.E. 1957. Effects of added sodium chloride, calcium chloride, magnesium chloride and citric acid on meat shrinkage at 70°C and of added sodium chloride on drip losses after freezing and thawing. *Food Technol.* **11**(2): 74-76.

Wismer-Pedersen, J. 1987. Water. In *The Science of Meat and Meat Products*. Price, J.F. and Schweigert, B.S. (Eds.). Food and Nutrition Press, Westport, CT. pp.141-154.

Wootton, A.E. 1986. Factors affecting the chilling rate of beef sides. In *IIR Meat Chilling*. Bristol, Paris. pp. 115-121.

Zaika, L.L., Wasserman, A.E., Monk, C.A. and Salay, J. 1968. Meat flavor. 2. Precedures for the separation of water-soluble beef aroma precursors. *J. Food Sci.* **33**:53-58.

CHAPTER 2

EFFECTS ON CHILLING EFFICIENCY AND WEIGHT CHANGE DURING VASCULAR INFUSION OF BEEF CARCASSES[1]

INTRODUCTION

Chilling of meat is recognized as an effective means to minimize microbial growth and prolong shelf life. Improvements in abattoir chilling technology for beef have traditionally focussed on maximizing throughput by reducing chilling time, and minimizing processing costs associated with energy consumption and moisture loss from meat during chilling.

EEC regulations require that beef should not be shipped after slaughter until the maximum temperature in the carcass side has been reduced to 7°C (Council of the European Communities, 1964). Adequate chilling typically requires up to 48h in conventional single stage chillers, and is associated with substantial shrinkage due to evaporative weight loss from carcass sides. Although rapid chilling using sub-zero air can improve chilling rate and reduce shrinkage, it has high capital and operating costs (James and Bailey, 1989). Water spray-chilling can also be used to reduce shrinkage, but it had no significant effects on the weight loss over 6 days of aging (Jones and Robertson, 1989).

---

[1] A version of this chapter has been presented at the International Congress of Meat Science and Technology, Aug. 1-6, 1993, Calgary, Canada.

Vascular infusion of pre-chilled water or solutions into intact beef carcasses immediately after slaughter can theoretically accelerate chilling and increase carcass yield. Heat removal during vascular infusion should be very efficient due to the large internal surface of the vascular system and reduced distance between muscle and infused chilling medium. Also, the relatively high muscle pH in hot carcasses should provide improved water holding capacity that can increase yield.

Vascular infusion could also be used to modulate post-mortem processes in which muscle is converted into meat. Thus, vitamin E could be added to prevent meat rancidity and colour loss, while addition of proteolytic enzymes, minerals, aminoacids, vitamins, and sugars could improve tenderness and flavour (Bradley *et al.*, 1987; Koohamaraie *et al.*, 1988; Asghar *et al.*, 1989 and Cunningham and Francis, 1981).

The aim of this study was to examine the effects of various vascular infusion parameters, including water temperature, flowrate, and total infused volume, on the chilling rate and weight change of carcass sides that are subsequently subjected to conventional air chilling.

MATERIALS AND METHODS

Forty young bulls were slaughtered and divided into two groups. The six animals in the first group were subjected to conventional slaughter and chilling procedures and served as the control group, while the 34 remaining animals were infused with different volumes of pre-chilled water at various temperatures and flowrates.

Immediately following stunning, whole beef carcasses, fitted with temperature and load sensors, were vertically suspended by means of straps (Fig. 2.1). Carcasses were then slaughtered and bled by severing the jugular veins, and a catheter was inserted into the left carotid artery immediately after bleeding. Chilling medium was pumped through the catheter into the vascular system, while fluid drained from the jugular veins was collected into a receiving vessel where the bulk temperature and total effluent weight were determined. During the infusion tests, the temperature, pressure, and flowrate of the chilling medium at the carcass inlet and/or outlet locations were electronically recorded by a computer data acquisition system (Model DT 280, Data Translation Inc., Marlboro, MA 01752-1192). Variations in carcass weight and ambient temperature during each infusion experiment were also recorded.

Groups of four to six animals having approximately equal mean live weight were assigned to eight different treatment combinations which consisted of two levels each of medium temperature (1 and 10°C) and total infused medium volume (10 and 20% of live-weight), and three levels of medium flowrate ranging from 12 to 17 l/min. Total infusion times ranged from 5 to 9 min. depending on carcass size and medium flowrate.

The temperatures of deep *semimembranosus* (SM) muscle and center of *longissimus dorsi* (LD) at 12th rib were determined immediately after dressing each carcass (45 minutes after slaughter) to prevent contamination. Since carcass temperatures remained essentially constant during the dressing period, temperature measurements taken immediately after dressing were considered to be representative of post-infusion carcass temperatures.

All left and right carcass sides were weighed after completion of dressing and prior to washing. Weight differences between infusion and control carcass sides were

investigated using analysis of variance with various models that included the effect of infusion parameters and their possible interactions (GLM procedure, SAS Institute Inc., Cary, NC, USA).

The sides were then chilled in air at 1°C and 1 m/s for 23 hours. During the first six hours in the cooler, carcasses were spray-chilled using a 60s cycle every 15 min. (24 cycles). Time-temperature profiles of the deep SM muscle and LD muscle centre at the 12th rib were recorded for each side using a multi-channel data logger (MPM- 4000/4013, Solomat Manufacturing Ltd., Bristol, U.K.) equipped with 16 type "K" thermocouples encased within stainless steel bayonet-type probes. Recorded temperatures were verified manually at 3 and 24 h post-mortem.

Side shrinkage was calculated as the percentage reduction in side weight based upon the initial hot unwashed mass of the side after dressing, and was assessed at 24 h and 6 day postmortem.

RESULTS AND DISCUSSION

Effect of Total Amount of Infused Medium on Carcass Temperature

Table 2.1 shows the effect of the total amount of infused water on the temperature fall of LD and SM muscles for carcasses of similar weight. Vascular infusion of 1°C water reduced LD muscle temperatures below that of control carcasses by 1.8 to 4.1°C at 45 min. postmortem. As the total amount of infused water was increased from 10% to 20% of the animal live weight, the loin muscle temperature decreased an additional 2.3°C. On the other hand, vascular infusion of 20% water reduced the deep SM muscle temperature by

only 1.6°C (as compared to 4.1°C for LD muscle), while infusion of 10% water barely reached the hind limb and had no significant effect on the temperature of deep SM muscle. The LD muscle experienced the greatest chilling effect, indicating that infused water likely reached the loin muscle shortly after entering the carcass. However, due to the vertical orientation of carcasses during infusion, water only reached the hind limb position after water equalling about 12% of the live weight had been infused. Thus, the hind limb part of the carcass experienced the least chilling effect since it was exposed to less water over a shorter period.

As shown in Fig. 2.2, 180 kg sides from carcasses infused with 20% pre-chilled water reached an LD muscle temperature of 7°C in the cooler 7 h faster than control carcasses. However, vascular infusion had little effect on the chilling rate of deep SM muscle.

The increased chilling rate of pre-infused LD muscle in the cooler was possibly due to evaporative cooling, since the latent heat required to evaporate moisture from the carcass surface must be provided by the meat. Excess water gained during vascular infusion may have continuously migrated to the carcass surface, transporting its own sensible heat while maintaining surface wetness, thus extending the evaporative cooling period.

Deep SM muscle temperature was found to slightly increase during the initial chilling period, as depicted in Figs. 2.2 and 2.3. A similar behaviour was reported by Bendall (1972). This phenomenon is possibly due to heat generation by anaerobic lactate formation and phosphocreatine (PC) breakdown during the early post-mortem period.

Temperature versus time relationships for infused and control carcasses (ca. 180 kg per side) were described within 2.5% accuracy by the following correlations:

LD Muscle Centre Temperature:

Control: $T = \exp(3.717 - 0.1434\ t)$ (2.1)

Infusion: $T = \exp(3.661 - 0.2638\ t)$ (2.2)

Deep SM Muscle Temperature:

Control: $T = \exp(3.890 - 0.0729\ t)$ $(t > 3\ h)$ (2.3)

Infusion: $T = \exp(3.832 - 0.0749\ t)$ $(t > 3\ h)$ (2.4)

where:

T = muscle temperature (°C)

t = time post-mortem (h).

Time-temperature profiles for SM muscle shown in Figs. 2.2 and 2.3 exhibit a characteristic lag period followed by exponential decay. A similar lag period has been reported by Moerman (1972) for deep muscle in conventionally chilled beef. This behavior could be explained in terms of theoretical solutions for the centre of conduction-heated solids. The slightly upward curvature of the exponential portion of these curves suggests a moderate increase in the thermal diffusivity of meat with temperature.

Effect of Infused Fluid Temperature on Chilling Rate

As shown in Table 2.2, increasing the infusion temperature from 1°C to 10°C resulted in moderatly higher LD muscle temperatures 45 min. after slaughter, but had no

significant effect on deep SM muscle temperatures. Similarly, in Fig. 2.3, it is shown that the LD muscle in carcasses infused at the lower temperature exhibited a moderately higher chilling rate in the cooler, while there was no significant difference for the SM muscle. Considering that the effect of infusion temperature on chilling rate was small, it may be desirable to use higher water temperatures to avoid the possibility of cold shortening, which can occur when the pre-rigor muscle temperature falls below about 10°C.

Effect of Flowrate on Carcass Temperature

As shown in Table 2.3, the infusion flowrate had little effect on carcass temperature in either LD or SM muscles. Similarly, post-infusion chilling responses in the cooler were essentially identical for carcasses that had been subjected to different flowrates, as shown in Figure 2.4. However, since the total amount of infused water was the same (20%) regardless of flowrate, higher flowrates resulted in proportionately shorter infusion times. The effects of flowrate and infusion volume can therefore be expected to cancel out, since the total amount of heat removed by vascular infusion is essentially the product of infusion time and the average or effective heat transfer rate. Thus, taking infusion time as inversely proportional to flowrate, and heat transfer rate as proportional to the 0.8 power of flowrate (turbulent flow inside tubes), the total heat removed would only be proportional to the -0.2 power of flowrate. Therefore, different flowrates should theoretically result in no significant differences on chilling rates, which agrees with the results presented in Table 2.3.

As observed during infusion, a minimum flowrate of about 12-15 l/min was required to achieve successful infusion, which was evidenced by contraction of the hind limb muscles (i.e., straightening out of the unshackled hind limb). Increasing the flowrate

beyond 15 l/min appeared to result in earlier water circulation to all parts of the carcass, which likely improved temperature reduction at the deep SM location. However, an excessive increase in flowrate might increase total water uptake to unacceptable levels.

Effect of Vascular Infusion on Weight Change of Beef Sides

As shown in Fig. 2.5, water uptake by carcasses depended on the total amount and temperature of the infused water. Carcasses infused with 10 and 20% water gained approximately 2 and 4% weight over control carcasses, respectively. This means that a typical 500 kg young bull carcass infused with 20% water gained about 20 kg moisture. Higher infusion temperatures of 10°C resulted in greater carcass moisture uptake ($P = 0.0078$). Infusion flowrates in the range of 12 - 15 l/min, however, had only a marginal effect on water uptake ($P = 0.5044$). Increasing the flowrate from 15 to 17 l/min may have resulted in excessive water uptake due to significant rupturing of blood vessels or damage of muscle tissue by the faster flowrate.

Tracer dye experiments revealed that water gained by carcasses during vascular infusion was predominantly retained in capillaries and the peripheral venous system. This excess water was subsequently lost by evaporation in the chiller. Sides that had been infused with 20% water exhibited shrinkage values ranging from 1.68% (3 kg moisture loss per 180 kg carcass side) during the first 24 h to 3.7% (6.7 kg moisture per 180 kg side) after six days, as shown in Table 2.4. Although these values are comparable to evaporative losses of 1-2% encountered in ideally controlled chillers (Collet and Gigiel, 1986), the overall or net shrink in beef sides processed by vascular infusion was negligible since evaporation losses in previously infused carcasses were balanced by the weight gained during infusion. This can have major economic implications, since the cost of evaporative

weight losses in a typical beef chilling operation can be considerably greater than the chilling energy cost (Collet and Gigiel, 1986).

Vascular infusion proved far more effective at minimizing shrinkage than alternative technologies, such as rapid chilling and water-spray chilling. Rapid chilling could only reduce 24 h shrinkage by 0.3% (Aalhus *et al.*, 1991) while water-spraying for 4 to 12 h resulted in reductions of 0.48 and 0.89%, respectively (Jones and Robertson, 1989). Neither rapid chilling nor water spraying had any effect on shrinkage after a 6 day conditioning period.

CONCLUSIONS

Vascular infusion of intact beef carcasses immediately after slaughter can increase cooler chilling rate and substantially reduce or eliminate carcass weight loss. Water temperature and total infused volume significantly influenced water uptake by muscle tissue, while infusion flowrate had only a marginal effect on water uptake. Vascular infusion substantially increased LD muscle chilling rate, but had little effect on that of SM muscle. Because the total volume of infusion fluid was constrained, increasing the flowrate had a negligible influence on chilling, since this resulted in a reduction of the fluid contact time in the carcass. However, a minimum flowrate of about 12-15 l/min was necessary to achieve adequate circulation to all parts of the carcass, particularly the hind limb. Increasing the flowrate beyond this level appeared likely to improve carcass temperature distribution and should result in higher chilling rates in the cooler, but might excessively increase total water uptake.

Table 2.1. Effect of total volume of infused 1°C water on carcass temperature 45 minutes after slaughter.

Total infused water (% of live weight)	Animal live weight (kg)	LD muscle centre temperature (°C)	Deep SM muscle temperature (°C)
0	596.9±78.0	39.1±0.8	40.2±0.4
10	570.5±13.8	37.3±0.8	39.7±0.6
20	579.3±12.7	35.0±0.5	38.6±0.6

Table 2.2. Effect of infused medium temperature on carcass temperature 45 minutes after slaughter.

Water temperature (°C)	Animal live weight (kg)	LD muscle centre temperature (°C)	Deep SM muscle temperature (°C)
1	579.3±12.7	35.0±0.5	38.6±0.6
10	565.5±13.5	35.7±0.4	38.8±0.8

Table 2.3. Effect of infusion flowrate on carcass temperature 45 minutes after slaughter.

Water temp.(°C) (20% of live wt.)	Medium flowrate (l/min)	Animal live weight (kg)	LD muscle temp. (°C)	SM muscle temp. (°C)
10	12.0	563.3±20.7	36.3±0.4	39.1±1.0
	14.8	534.6±16.4	35.9±0.8	38.7±0.2
	16.8	560.3±10.4	35.8±0.7	38.5±0.3
1	12.0	535.9±10.0	35.0±0.3	38.9±0.4
	14.8	535.3±11.6	35.8±0.8	39.6±0.2
	16.8	579.0±12.7	35.2±0.5	38.8±0.4

Table 2.4. Carcass weight loss in the chiller.

Total infused water (% of animal live weight)	Carcass side wt. (kg)	24 h shrinkage (%)	6 day shrinkage (%)
20	180.0±10.3	1.68±0.18	3.70±0.31

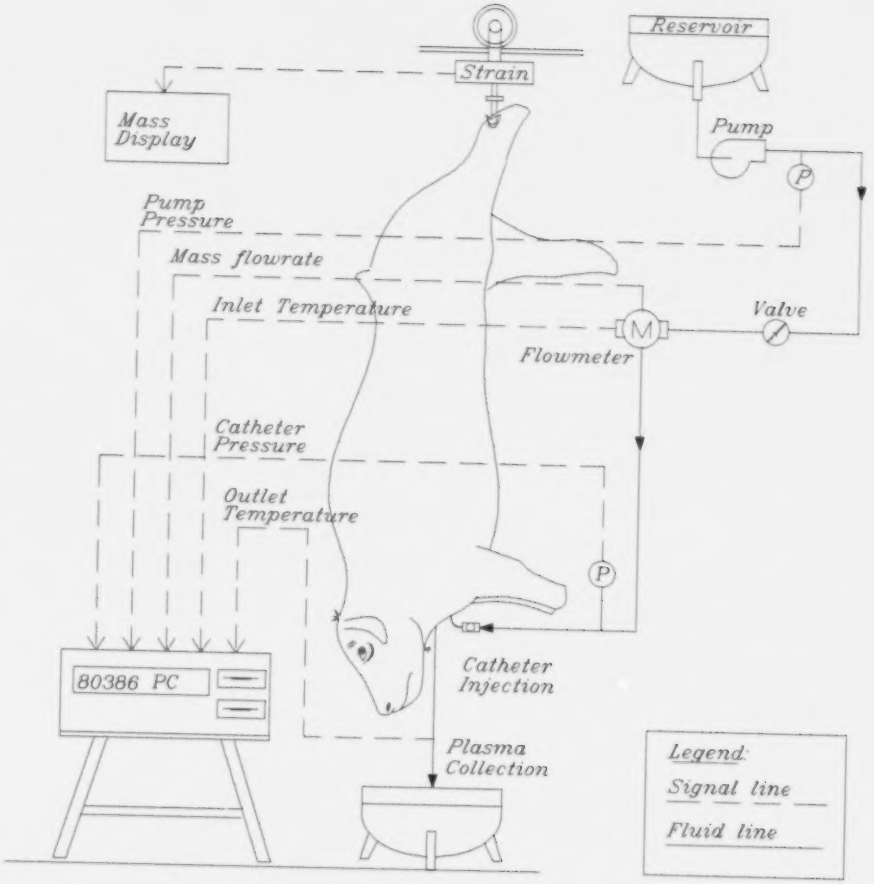

Figure 2.1. Schematic of experimental arrangement showing fully intact beef carcass and vascular infusion apparatus and instrumentation.

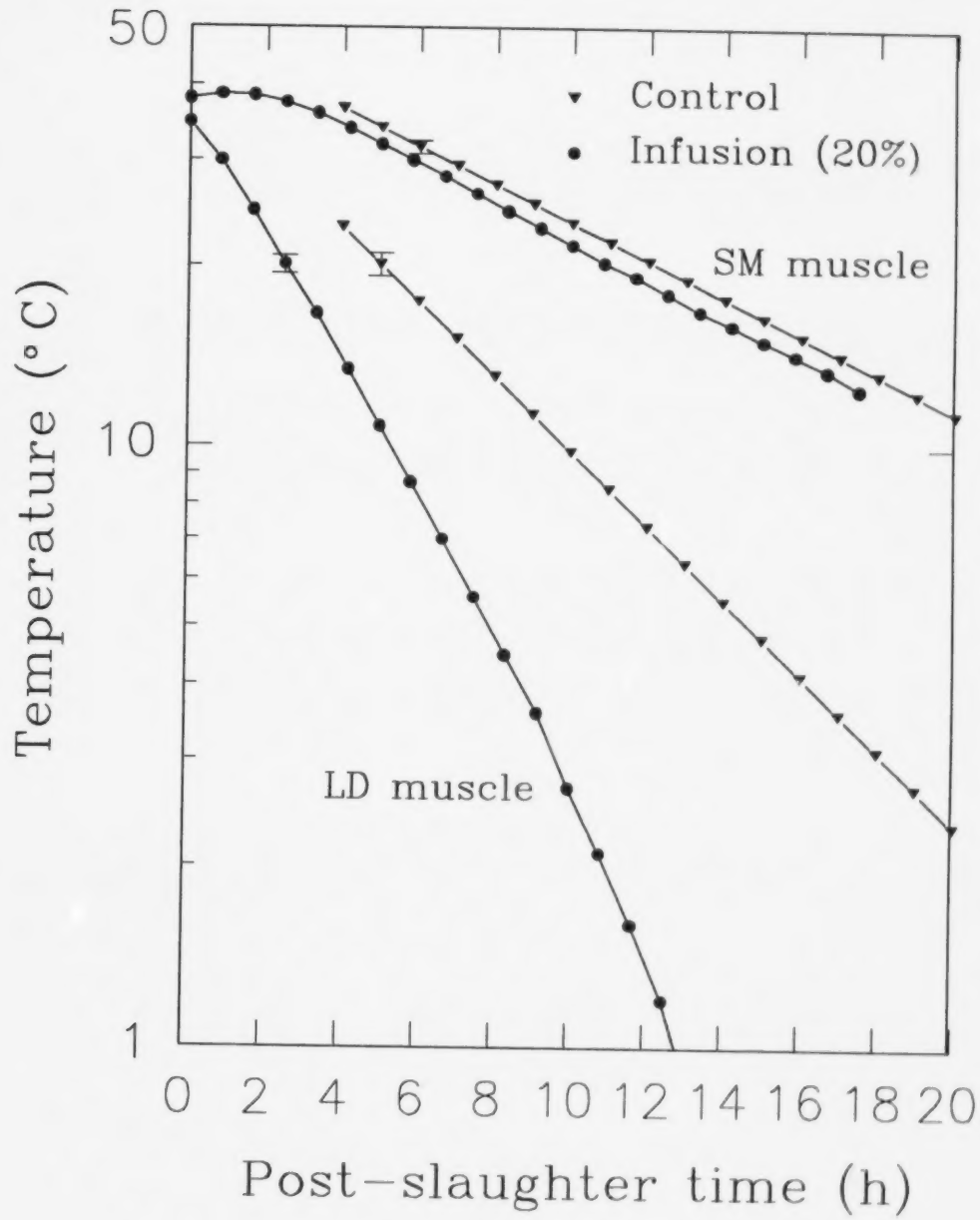

Figure 2.2. **Time-temperature profiles in muscle processed with and without vascular infusion.**

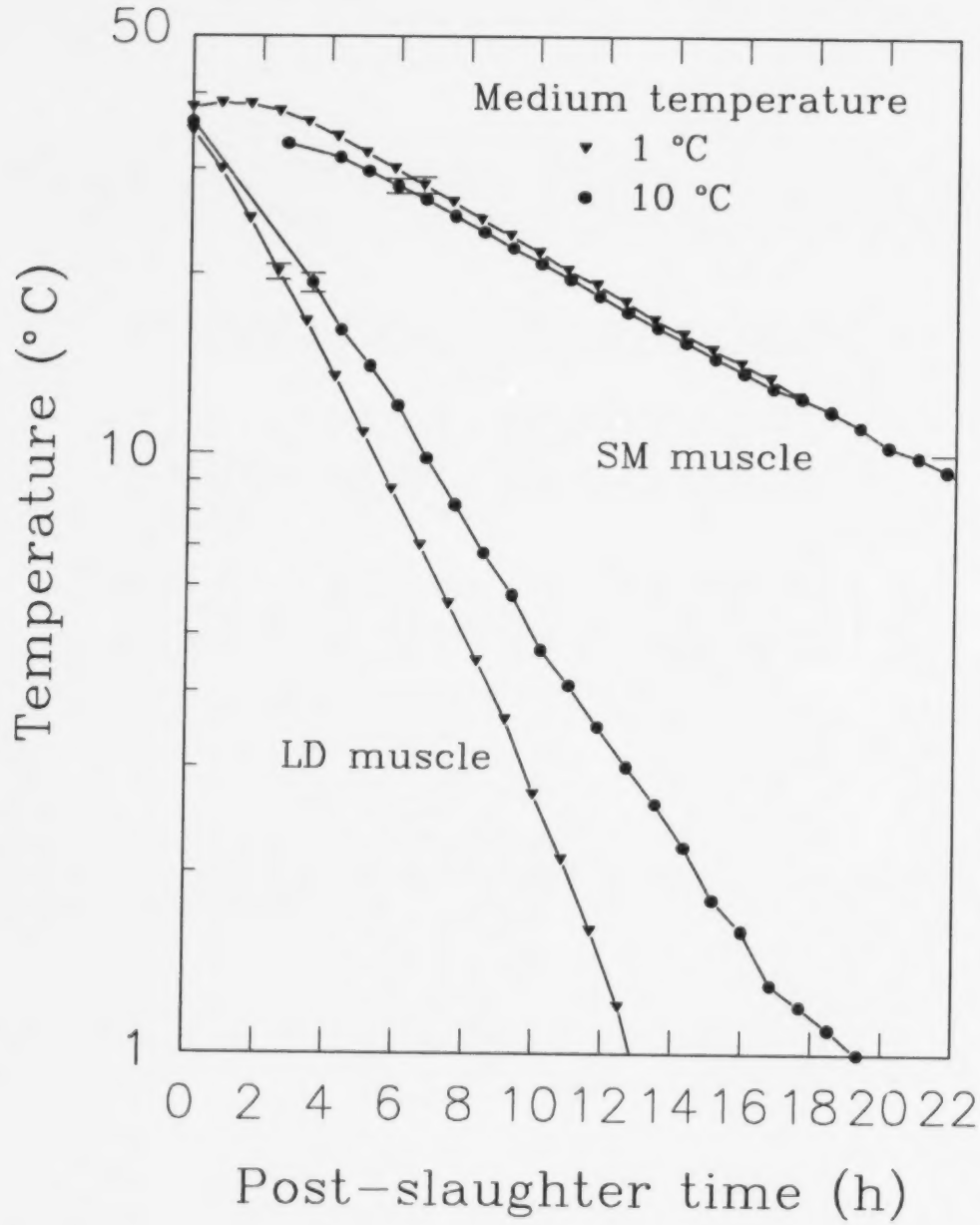

Figure 2.3. **Time-temperature profiles in muscle processed by vascular infusion using water at 1 and 10°C.**

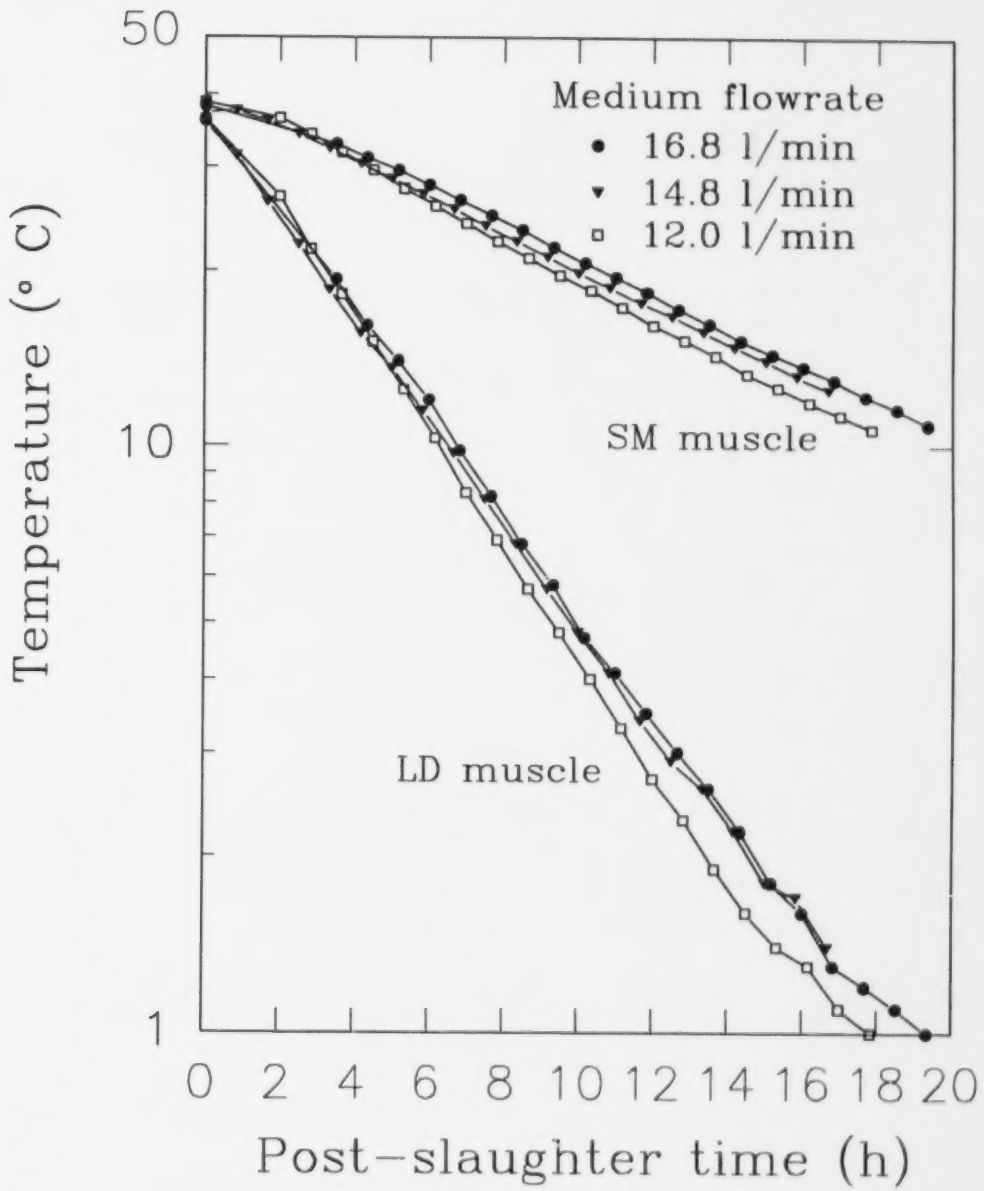

Figure 2.4. **Time-temperature profiles in muscle processed by vascular infusion using 10°C water at three flowrates.**

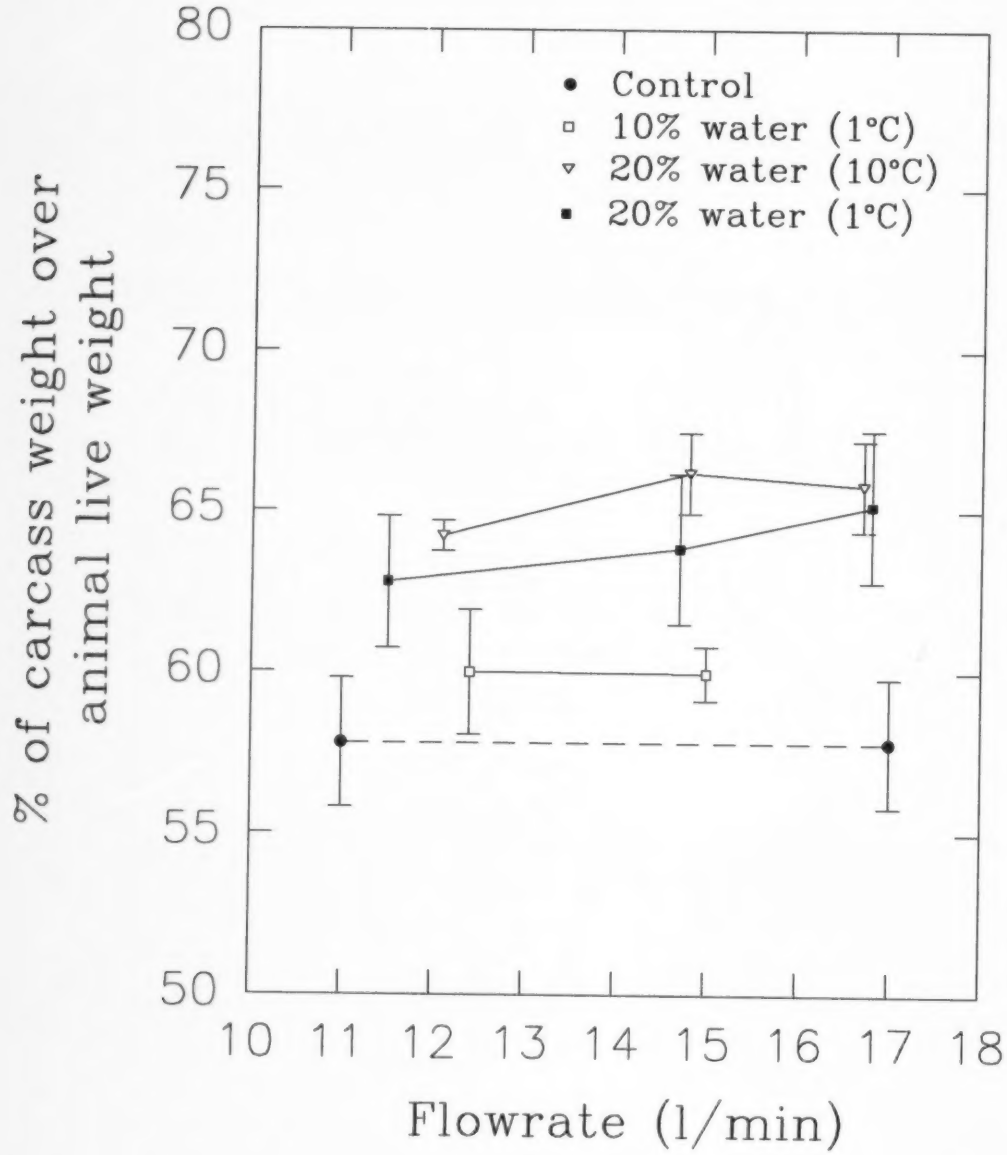

Figure 2.5. **Carcass yield for different combinations of infusion parameters.**

REFERENCES

Aalhus, J.L., Tong, A.K.W., Robertson, W.M., and Jones, S.D.M. 1991. The effect of rapid chilling on beef quality. Presented at the 37th International Congress of Meat Science and Technology, September 1-6. Kulmbach, Germany.

Asghar, A., Gray, J.I., Booren, A.M., Miller, E.R., Pearson, A.M., Ku, P.K. and Buckley, D.J. 1989. Influence of dietary vitamin E on swine growth and meat quality. *Int. Congr. Meat Sci. Technol.*, **35**: 1065-1070.

Bendall, J.R. 1972. In: *Meat Chilling- Why and How?* Cutting C.L. (Ed), Meat Research Institute, Bristol, pp. 12.1-12.5.

Bradley, R., O'Toole, D.T., Wells, D.E., Anderson, P.H., Hartley, P., Berett, S., Morris, J.E., Tnsch, C.G. and Hayward, E.A. 1987. Clinical biochemistry and pathology of mature beef cattle following antemortem intravenous administration of a commercial papain preparation. *Meat Sci.* **19**: 39-51.

Collett, P. and Gigiel, A.J. 1986. Energy usage and weight loss in beef and pork chilling. In *IIR Meat Chilling*. Bristol, Paris, pp. 171-177.

Council of the European Communities 1964. Council Directive of 26 June, 1964 on health problems affecting intra-community trade in fresh meat (64/433/EEC).

Cunningham, F.E. and Francis, C. 1981. Injectable-detectable: new process offer more tender poultry. *Feedstuffs*, **53** (Sept.): 33.

James, S.J. and Bailey C. 1989. Process design data for beef chilling. *Int. J. Refrig.*, **12** (January): 42-49.

Jones, S.D.M. and Robertson, W.M. 1988. The effects of spray-chilling carcasses on the shrinkage and quality of beef. *Meat Sci.*, **24**: 177-188.

Koohmaraie, M., Babiker, A.S., Schroeder, A.L., Merkel, R.A. and Dutson, T.R. 1988. Acceleration of postmortem tenderization in ovine carcasses through activation of Ca^{++}-dependent proteases. *J. Food Sci.*, **53**: 1638-1641.

Moerman, P.C. 1972. In: *Meat Chilling-Why and How?*, Cutting C.L. (Ed.), Meat Research Institute, Bristol, pp. 14.51-14.53.

CHAPTER 3

MODELING HEAT AND MASS TRANSFER CHARACTERISTICS DURING VASCULAR INFUSION OF BEEF CARCASSES

INTRODUCTION

Associated with conventional chilling of beef carcasses in commercial abattoirs are significant problems arising from unsatisfactory chilling rates and evaporative moisture loss (Collet and Gigiel, 1986). In Canada, annual losses due to evaporative moisture loss have been estimated at 32 million dollars for chilled beef carcasses (Greer and Jones, 1993). Consequently, there is increasing demand for novel chilling technologies and accelerated chilling systems in order to reduce cooling time and carcass shrinkage.

It is generally accepted that the abattoir chilling is an energy-intensive process, and small energy savings can thus have a significant effect on the overall operating cost to run a meat processing facility. However, as shown by Bowater (1986), carcass weight loss during conventional chilling has a greater impact on profitability than energy consumption.

Rapid chilling methods using high velocity air at temperatures between -15 and -70^{o}C are considered as a viable means to decrease chilling time and weight loss (Aalhus *et al.*, 1991; Bowater, 1986 and Watt and Herring, 1974). Also, since the use of sub-zero temperature air facilitates heat removal, the consequent rapid decline in surface temperature produces a greater hygienic effect, resulting in longer product shelf life (Gill and Jones, 1992). Although the savings from weight loss reduction may be attractive, the

capital and operating costs of rapid chilling are high (Bowater, 1986). On the other hand, risks of cold shortening due to rapid chilling could be prevented by adoption of early post-mortem electrical stimulation (Locker, 1985). Substantial freezing of pre-rigor muscle would lead to an increased drip loss on final cutting (Gigiel *et al.*, 1985). To prevent this, rapid chilling systems maintain very low temperatures only during the initial few hours of chilling, which removes most of the sensible heat from beef sides. This is followed by conventional chilling to further reduce the temperature at the thermal center of the beef side (i.e., deep hip), and to equilibrate the carcass temperature.

Water spray chilling is an alternative technology to minimize evaporative weight losses. This process uses a combination of air movement and applied water sprays during the initial phase of chilling, and only air movement for the rest of chilling. Jones and Robertson (1989) reported that carcass shrinkage over 24 h using spray-chilling (4 cycles per hour; 60 s/cycle) was reduced by 0.48% to 1.48% when water spraying time was increased from 4 to 12 h, respectively. Due to the strong susceptibility of warm and wet carcass surface to bacterial proliferation, investigations of spray-chilling on beef quality and storage life were carried out by Jones and Robertson (1988, 1989), Greer *et al.* (1990) and Greer and Jones (1993). Their work showed that spray-chilling had no apparent detrimental effects on muscle quality, bacteriology and retail life. This may encourage the meat industry to use this technique to gain the benefit of reduced weight loss without concern for compromising meat quality or increasing spoilage loss. However, Jones and Robertson (1989) indicated that the advantage of reduced shrinkage may become less significant as a result of evaporation that occurs during the subsequent 6 day carcass conditioning period.

Vascular infusion of intact beef carcasses using pre-chilled water improved both early post-mortem chilling rate and carcass yield, as presented by Wang *et al.* (1993).

Further modeling and quantification of heat and mass transfer associated with vascular infusion of pre-chilled water is necessary in order to fully characterize the effectiveness of this novel process.

The aim of this work was to develop an engineering model for characterizing momentum, mass and heat transfer in intact beef carcasses undergoing chilling by vascular infusion of water, as well as to predict the temperature history of intact muscle subjected to vascular infusion according to known operating variables.

MATHEMATICAL MODEL

Thermal Energy and Mass Balances

A schematic diagram of the experimental layout is presented in Figure 3.1. The infusion process was modeled as an open system in which heat and mass transfer takes place. The transient heat balance for the carcass is described as follows:

$$W_{A0}\frac{dH_A}{d\theta} = F_i C_{pw}(T_{wi} - T_{wo}) \qquad (3.1)$$

where:

C_{pw} = Heat capacity of chilling medium (J / kg ·°C)

F_i = Medium flowrate at the inlet (kg /s)

H_A = Average enthalpy of a intact carcass (J /kg)

T_{wi} = Inlet temperature of chilling medium (°C)

T_{wo}= Outlet temperature of chilling medium (°C)

W_{A0} = Animal live weight (kg)

The enthalpy change for the carcass (ΔH_A) can be obtained by integration of Eq. (3.1), and the average carcass temperature immediately after infusion can be calculated from the change in carcass enthalpy (ΔH_A), as follows:

$$\Delta H_A = \frac{F_i C_{pw} \Delta\theta}{W_{A0}} (T_{wi} - \overline{T}_{wo}) \tag{3.2}$$

$$\Delta H_A = C_{pA} (T_{Af} - T_{Ai}) \tag{3.3}$$

where:

C_{pA} = Mean heat capacity of the carcass side

T_{Ai} = Initial temperature of a intact carcass (°C)

T_{Af} = Temperature of an intact carcass immediately after infusion (°C)

$\overline{T}_{wo}$ = Average (bulk) value of T_{wo}

The mean heat capacity of the carcass side is defined as:

$$C_{pA} = \varepsilon_m C_{pm} + \varepsilon_b C_{pb} + \varepsilon_f C_{pf} \tag{3.4}$$

Here ε_m, ε_b, ε_f are the mass fractions of lean meat, bone and fat for the carcass side, respectively. C_{pm}, C_{pb} and C_{pf} are the heat capacities of lean meat, bone and separable fat, respectively.

The fraction of thermal energy removed by vascular infusion relative to the amount of thermal energy required to reduce the carcass to a uniform temperature of 7°C is calculated as:

$$\eta = \frac{T_{Ai} - T_{Af}}{T_{Ai} - 7} \times 100 \tag{3.5}$$

Heat Transfer Model

The total chilling process was conceptualized as a mass of meat containing a parallel bundle of internal pipes (i.e., similar to a tube-type heat exchanger). Since vascular infusion only lasts a few minutes and the carcass temperature decline during this period is small, the infused water can be assumed to exert a uniform chilling effect throughout the entire carcass. This is a good approximation since $(T_{Ai} - T_{Af}) << (T_w - T_A)_{lm}$.

Only part of the total heat removed by vascular infusion is actually used for chilling the dressed carcass. Defining a carcass yield, ϕ, as the ratio of carcass side weight over total animal live weight, the heat balance and heat transfer equations for a dressed carcass side can be written as follows:

$$\phi F_i C_{pw}(T_{wi} - T_{wo})d\theta = \phi W_{A0} C_{pA} dT_A$$

$$= UA \frac{(T_{wi} - T_A) - (T_{wo} - T_A)}{\ln \dfrac{T_{wi} - T_A}{T_{wo} - T_A}} d\theta \qquad (3.6)$$

where A is heat transfer area, U is the average heat transfer coefficient and T_A is the carcass temperature. Due to the short infusion time, it was assumed that the product of heat transfer coefficient (U) and heat transfer area (A) remains constant during the infusion period.

Eliminating T_{WO} from Eq. (3.6) and integrating, the following unsteady-state heat transfer equation was derived:

$$\ln\left(\frac{T_{wi} - T_{Ai}}{T_{wi} - T_{Af}}\right) = \frac{F_i C_{pw} \theta}{W_{A0} C_{pA}} \left[1 - \exp\left(-\frac{UA}{\phi F_i C_{pw}}\right)\right] \qquad (3.7)$$

Momentum Energy Balance

An adequate fluid pressure at the catheter inlet is very important to ensure that water circulates to all parts of the carcass, particularly the hind limb. A momentum energy balance between the catheter inlet (1) and outlet (2) of the vascular system in Fig. 3.1 can be written as follows:

$$\frac{P_1}{\rho g} + \frac{u_1^2}{2g} + Z_1 = \frac{P_2}{\rho g} + \frac{u_2^2}{2g} + Z_2 + h_f \qquad (3.8)$$

where:

h_f = Friction head (m)

P = Fluid pressure (kPa)

u = Fluid velocity (m/s)

Z = Fluid potential energy head (m)

ρ = Fluid density (kg/m^3)

Since the kinetic head and potential head changes are negligible in this case, the friction loss in the vascular system can be calculated as:

$$h_f = \frac{P_1 - P_2}{\rho g} \qquad (3.9)$$

A friction factor for the vascular network, K_f, can be defined by the following equation:

$$h_f = K_f \frac{u_1^2}{2g} \qquad (3.10)$$

Experimental K_f values obtained from Eq.(3.10) can then be used to predict the required pump pressure under different operating conditions.

MATERIALS AND METHODS

In this study, groups of four to six animals having similar mean live weight were assigned to eight different combinations of treatments that consisted of two levels of temperature (1 & 10°C), two levels of total infused volume (10 & 20% of animal live weight), and three levels of medium flowrate (12, 15, & 17 l/min.).

Vascular infusion was conducted immediately after slaughter and bleeding. Pre-chilled water was pumped through intact beef carcasses by inserting a catheter into the left carotid artery. The inlet water conditions including temperature, density, flowrate, and total volume of infused water were measured by a Micro Motion instrument (7070 Winchester Circle, Boulder, CO, USA) containing a mass flow meter (Model D100s-ss), a remote digital indicator (Model D10-RT) and a liquid densitometer (Model DT-7) for density/temperature measurements. The pressure measurements were carried out by two liquid pressure transducers (Model PX236, Omega Engineering Inc. Stamford, CT, USA) at the pump outlet and the catheter inlet. The water effluent was collected by a funnel from the severed jugular veins into a receiving vessel where the bulk temperature and total effluent weight were manually measured. The temperature at the outlet of the vascular system was determined by a type "K" thermocouple encased within a stainless steel bayonet-type probe. Flowrate, total infused volume, pressure, as well as inlet and outlet infusion temperature were monitored continuously using a computer data acquisition system consisting of a data transducer (Model DT-280, Data translations, Marlboro, MA 01752-1192) and a 386/33 personal computer.

Intact carcasses were vertically suspended by means of straps as shown in Fig. 3.1. Changes in carcass weight were determined by a calibrated weight scale (Model DF2000, Reliable Scale Corporation, Calgary, AB, Canada). Carcass weight histories during

infusion at different fluid flowrates are shown in Fig. 3.2. All carcass weight data were normalized with respect to animal live weight, and water uptake rates (R_w) were calculated from the slope of the weight change curves as:

$$R_w = \frac{1}{W_{A0}} \frac{dW_A}{d\theta} \tag{3.11}$$

After infusion, carcasses were subjected to conventional dressing and chilling processing combined with intermittent water spray (1°C, four 60-sec cycles/hr) for the initial 4h of chilling. Temperatures of specific muscle groups and side weights for both left and right sides were determined after infusion. Further details are provided by Wang *et al.* (1993).

RESULTS AND DISCUSSION

Energy Removal by Vascular Infusion

Figure 3.2 shows carcass weight histories during infusion with different flowrates of pre-chilled water. Water retention within the intact carcass results in weight gain, mostly due to water located in the abdominal cavity (i.e., rumen and intestines). Only a small fraction of the total retained water was bound by muscle tissue, as revealed by Wang *et al.* (1993). Therefore, the abdominal cavity and enclosed organs can be considered a reservoir, as depicted by the flow model in Fig. 3.3.

In Fig. 3.3, F_r represents the rate of water retention ($dW_A/d\theta$), while F_o and F_i are water flowrates at the outlet and inlet locations, respectively. Results presented in Figure 3.2 clearly show that the rate of water retention and outlet flowrate during infusion

are constant (i.e., linear weight increase). Water retention rates (slopes) at different infusion flowrates are summarized in Table 2.1. It was observed that increased flowrate results in an increased rate of water uptake.

Carcass composition (contents of fat, lean meat and bone) and specific heats for lean beef, fat and bone are shown in Table 3.2. The specific heats used in this study were those given by Morley (1972), and tissue composition of dressed bull carcasses were taken from McGinnis *et al.* (1993). The mean specific heat of bull carcass sides was calculated by Eq. (3.4).

The total amount of heat lost by the animal during infusion (ΔH_A) was obtained from Eq. (3.2). Eq. (3.3) was then used to calculate the final carcass side temperature after infusion from ΔH_A and C_{pA}, the mean specific heat for the carcass side. The results are presented in Table 3.3. Vascular infusion of 1°C water totaling 10 and 20% of animal live weight reduced side temperatures from ca. 40°C to 37.3 and 35.0°C, respectively. Similarly, a final temperature of 36.4°C was obtained by infusion of 10°C water at a level of 20% of animal live weight. Calculated carcass temperatures were found to agree with experimental LD muscle values, which are generally considered as representative of the average carcass temperature. The higher SM muscle temperature, on the other hand, represents the slowest chilling regime within the carcass side.

The fractions of thermal energy removed by vascular infusion (Eq. 3.5) are also shown in Table 3.3. Vascular infusion removed as much as 14.3% of the total thermal energy required to reduce carcass temperatures down to 7°C. The amount of heat removed was found to be proportional to the total amount of infused water (η= 7.9% at 10% of ALW vs. 14.3% at 20% of ALW). Also, lower temperatures resulted in increased heat removal (η= 14.3% at 1°C vs. 10.9% at 10°C).

Heat Transfer Model Predictions

Temperature decline histories in muscle were predicted by Eq. (3.7) assuming uniform initial muscle temperature and a 60% carcass yield. Predicted and experimental muscle temperatures agreed within ±0.5%, as shown in Table 3.3.

Experimentally determined values of the model parameter UA , the product of heat transfer coefficient (U) and heat transfer area (A) within the vascular system (Eq. 3.7), are presented in Table 3.4 for different infusion flowrates. The increase in UA with flowrate can be attributed to both U and A. The heat transfer coefficient is expected to increase proportionally to the 0.8 power of flowrate, as for turbulent flow in pipes. Higher flowrates may also contribute to force infused water into a larger portion of the vascular network, thus increasing the heat transfer area.

Friction Loss in the Vascular System

As discussed above, adequate circulation to all parts of the carcass is essential for effective heat transfer between the infusion medium and muscle tissue. One means used to assess water circulation was to observe infusion-induced muscle contractions in the elevated unshackled hind limb, which tended to straighten out when the infusion medium reached this extremity. On this basis, it was observed that a minimum flowrate of 12 l/min was required for successful infusion.

Since the infusion medium at the outlet of the vascular system was at atmospheric pressure, the catheter pressure reflected the energy required to overcome flow resistance within the vascular network. In determining the flow resistance for each carcass and infusion treatment, it was assumed that changes in both kinetic and potential energy of the

medium between the carotid artery inlet and jugular vein outlet were negligible. Therefore, the inlet pressure was taken as a measure of the energy consumed by frictional resistance within the blood vessels. As shown in Fig. 3.4, both pump discharge pressure and catheter (inlet) pressure increase as medium flowrate increases. However, pump and catheter pressures remain constant during infusion, indicating that the internal resistance of the vascular system is essentially constant throughout the infusion process.

The friction loss and friction factor were calculated from Eqns. (3.9) and (3.10), respectively. Experimental values for the friction factor are presented in Table 3.5. It was observed that temperature exerts a considerable effect on the flow resistance. The friction factor associated with infusion of water at 1°C was much higher than that for water at 10°C. This may be partly explained by the contraction of blood vessels when exposed to lower temperatures, a natural heat conservation mechanism in mammals. As well, collapsed blood vessels resulting from bleeding may still contain blood which can clot more readily when exposed to water at lower temperature. Clotted blood might reduce the cross-sectional area of the affected blood vessels, thereby contributing to the observed increase in pressure required to achieve the desired flowrate.

CONCLUSIONS

Vascular infusion of pre-chilled water effectively removed up to 14.3% of the total carcass heat above 7°C in less than 6 minutes, depending on medium temperature and flowrate. A mathematical model was developed to describe heat transfer, water uptake, and frictional pressure drop during vascular infusion. The carcass was conceptualized as a multi-tube heat exchanger, characterized by a single parameter (U·A) which depended on medium flowrate. The model adequately predicted muscle temperature decline during vascular infusion as function of medium flowrate, temperature, infusion time and carcass size. Predicted and experimental temperatures at the end of the vascular infusion process were found to agree within 0.5%.

The frictional resistance to flow within the vascular network (K_f) was calculated from pressure drop measurements with the help of a mechanical energy balance. Friction factors were found to be significantly higher at lower infusion temperatures, possibly due to temperature-induced contraction of vessels. Within the relatively narrow range of animal weights used in the present study, carcass size had no measurable effect on the friction factor.

Table 3.1. Rate of carcass weight change during infusion at different flowrates.

Rate of water retention (1/s)	Flowrate (l/min.)		
	12.0	14.8	16.8
$R_W = \frac{1}{W_{A0}} \frac{dW_A}{d\theta}$	0.015±0.003	0.020±0.001	0.022±0.002

Table 3.2. Mass fractions and specific heats of different carcass side components.

	Lean meat	Bone	Fat	Reference
Mass fraction of bulls (half carcass) (kg/kg_{ALW})	0.65	0.17	0.17	McGinnis *et al.* (1993)
Mass fraction of steers (half carcass) (kg/kg_{ALW})	0.70	0.15	0.15	Bailey & Cox (1976) and Gac & Tupin (1964)
Specific heat (kJ/kg·K)	3.43	2.09	2.89	Ordinanz (1946)
	3.56	2.51	3.89	Morley (1972)
	3.52	N/A	N/A	Potter (1978)
	3.51	N/A	N/A	Charm (1971)
	3.58	N/A	N/A	Heldman (1977)

Table 3.3. Carcass temperatures and fraction of heat removed during vascular infusion.

Water temperature (°C)	Experimental process characteristics		Total infused water (% of animal live weight)		
			0	10	20
1	Carcass side temperature (°C) (Experimental)		40	37.4±0.2	35.3±0.4
	Carcass side temperature (°C) (Model)		40	37.6±0.1	35.4±0.1
	Specific muscle temperature (°C)	LD	39.1± 0.8	37.3±0.8	35.0±0.5
		SM	40.2±0.4	39.7±0.6	38.6±0.6
	Fraction of heat removal η (%)		0	7.9±0.5	14.3±1.1
10	Carcass side temperature (°C) (Experimental)		-	N/A	36.4±0.3
	Carcass side temperature (°C) (Model)		-	N/A	36.16±0.1
	Specific muscle temperature (°C)	LD	-	N/A	35.7±0.4
		SM	-	N/A	38.8±0.8
	Fraction of heat removal η (%)		-	N/A	10.9±0.9

Table 3.4. Overall heat transfer parameter (UA) for different flowrates.

Infusion flowrate (*l* /min)	Model parameter (UA) (W/K)
12.0	0.40 ± 0.08
14.8	0.53 ± 0.08
16.8	0.56 ± 0.06

Table 3.5. Experimental friction factors of the vascular system.

Water temperature (^{o}C)	Friction factor, K_f
1	36.02 ± 1.23
10	21.25 ± 1.60

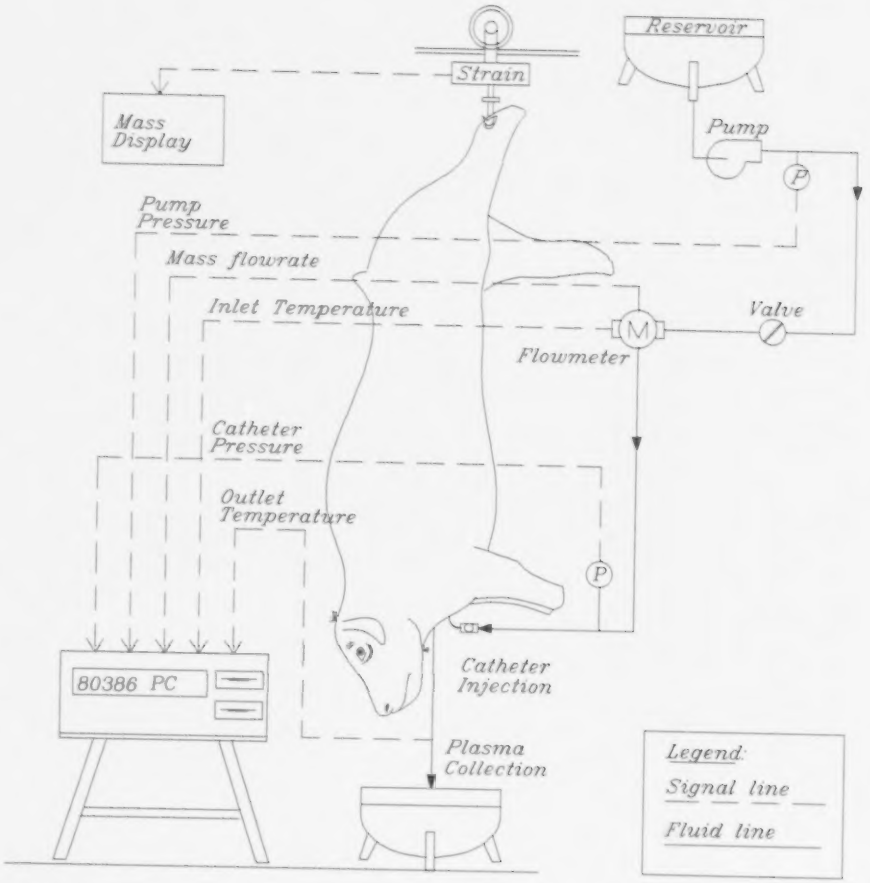

Figure 3.1. Schematic of experimental arrangement showing fully intact beef carcass and vascular infusion apparatus and instrumentation.

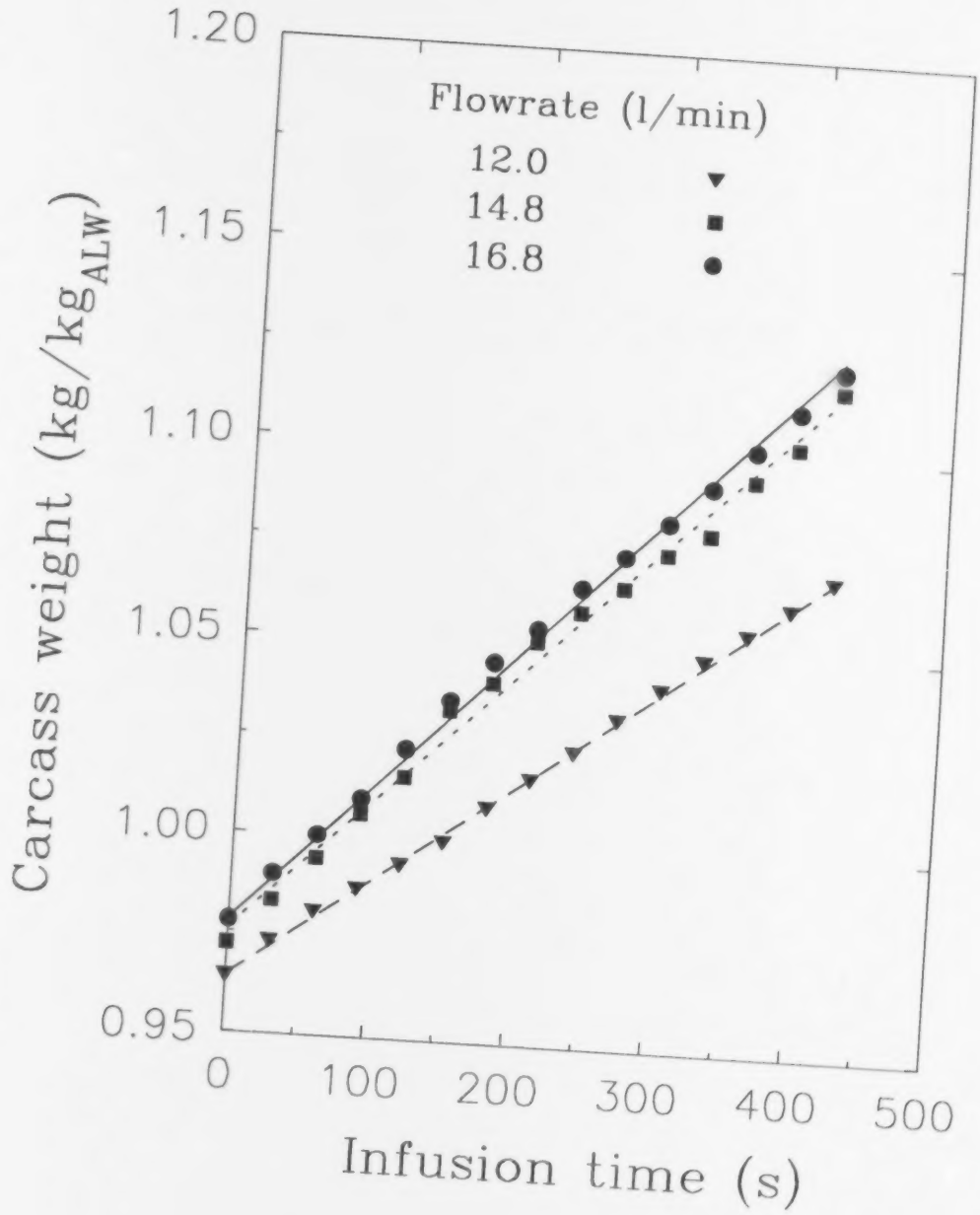

Figure 3.2. **Variation of carcass weight during vascular infusion at different flowrates.**

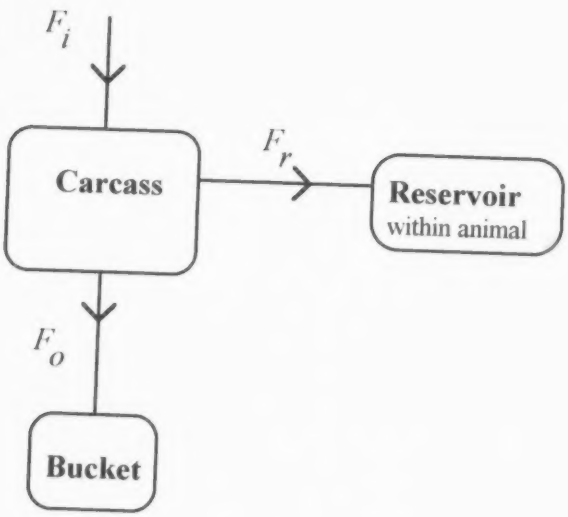

Figure 3.3. Flow model for vascular infusion of beef carcasses.

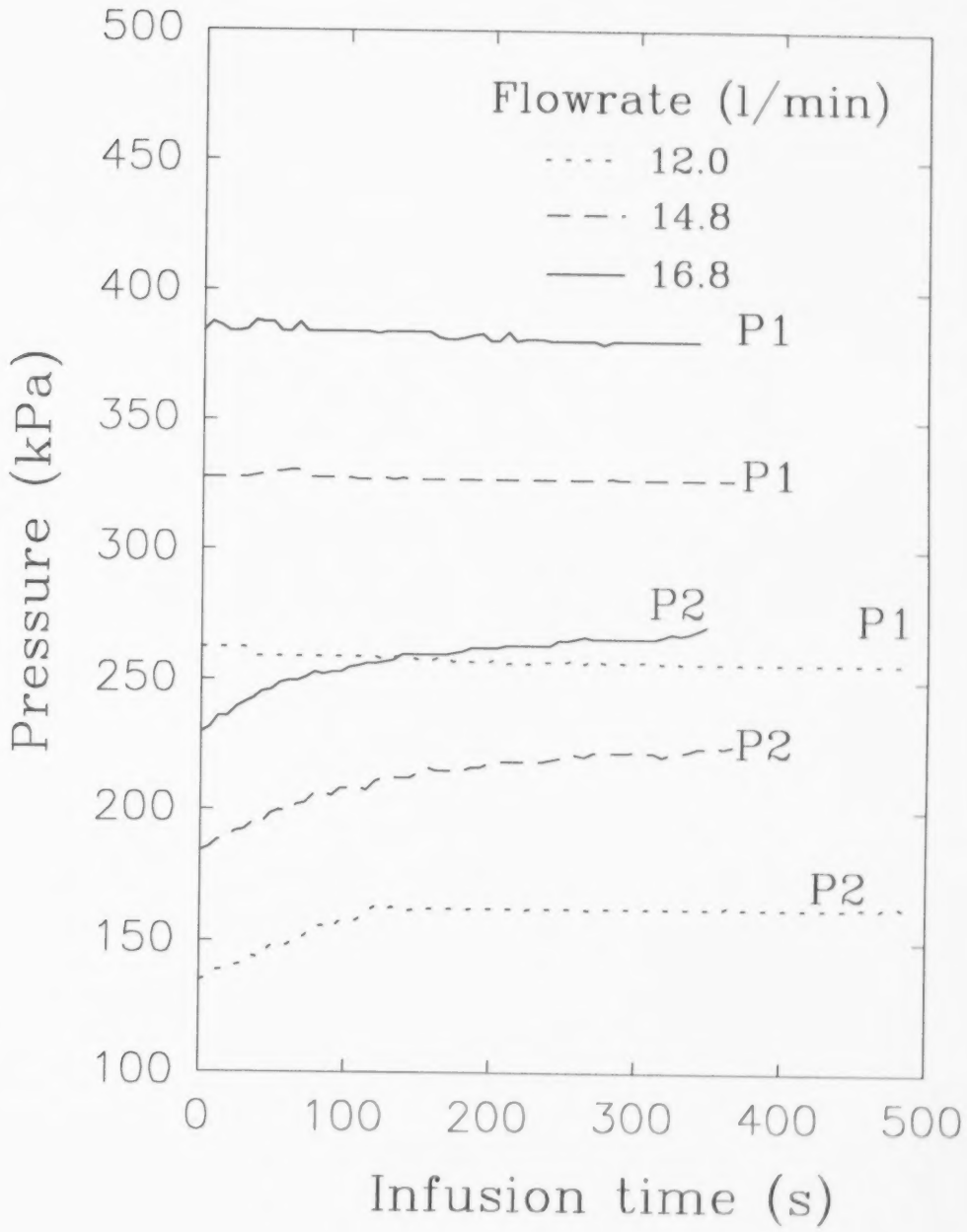

Figure 3.4. **Water pressure versus time profiles at pump outlet (P1) and catheter tip (P2).**

REFERENCES

Aalhus, J.L., Tong, A.K.W., Robertson, W.M. and Jones, S.D.M. 1991. The effect of rapid chilling on beef quality. Presented at the 37th International Congress of Meat Science and Technology, Set 1-6. Kulmbach, Germany.

Bailey, C. and Cox, R.P. 1976. The chilling of beef carcasses. *MRI Memoire*. No. 737.

Bowater, F.J. 1986. The economics of modern beef chilling systems. In *Recent Advancements and Develoments in the Refrigeration of Meat by Chilling.* Proceedings of the International Institute of Refrigeration, Commission C2: 165-171.

Charm, S.E. 1971. The influence of rate of chilling in the development of rigor and cold-shortening. *Meat-chilling- Why and How?*. Cutting C. L. (Ed.). Meat Research Institute, Langford, Bristol, pp. 3.1-3.6.

Gac, A. and Tupin, J.P. 1964. *Bulletin Technique du Genie Rural.* No.69.

Gigiel, A.L., Swain, M.V.L. and James, S.J. 1985. Effect of chilling hot boned meat with solid carbon dioxide. *J. Food Technol.* **20**: 615-622.

Gill, C.O. and Jones, T. 1992. Assessment of the hygienic efficiencies of two commercial processes for cooling pig carcasses. *Food Micro.* **9**(4): 335-343.

Greer, G.G., Jones, S.D.M., Dilts, B.D. and Robertson, W.M. 1990. Effect of spray-chilling on the quality, bacteriology and case life of aged carcasses and vaccum packaged beef. *Can. Food Sci. Technol. J.* **23**: 82-86.

Heldman, D.R. 1977. *Food Process Engineering.* AVI Publishing Inc., Westport CT. pp 384.

James, S.J. and Bailey C. 1989. Process design data for beef chilling. *Int. J. Refrig.* **12** (Janunary): 42-49.

Jones, S.D.M. and Robertson, W.M. 1989. The effects of spray-chilling carcasses on the shrinkage and quality of beef. *Meat Sci.* **24**: 177-188.

Jones, S.D.M. and Robertson, W.M. 1988. The effects of shrouding on the appearances of spray-chilled beef carcasses. *Can. Food Sci. Tech. J.* **21**: 112-114.

Koohmaraie, M. , Babiker, A.S., Schroeder, A.L., Merkel, R.A. and Dutson, T.R. 1988. Acceleration of postmortem tenderization in ovine carcasses through activation of Ca^{++}-dependent proteases. *J. Food Sci.* **53**: 1638-1641.

McGinnis, D.S. and Aalhus, J.L., Gariepy, C., Chabot, B., and Jones, S.D.M. 1993. A modified hot processing strategy for beef: Reduced electrical energy consumption in carcass chilling. Submitted to *Meat Res. Int'l* for publication.

Morley, M. J. 1972. Thermal properties of meat. *Meat Chilling- Why and How?*. Cutting C. L. (Ed.). Meat Research Institute, London, UK.

Potter, N.N. 1978. *Food Science.* 3rd. Edition. AVI Publishing Inc., Westport CT.

Wang, Y.W., McGinnis, D.S., Segado, R.R. and Jones, S.D.M. 1993. Vascular infusion of beef carcasses: Effect on chilling efficiency and weight change. Presented at the 39th International Congress of Meat Science and Technology, Aug. 1-6. Calgary, Canada.

Watt, D.B. and Herring, H.K. 1974. Rapid chilling of beef carcasses utilizing amonia and cryogenic systems: Effects on shrink and tenderness. *J. Anim. Sci.* **38**: 928-934.

CHAPTER 4

RESIDENCE TIME DISTRIBUTION IN VASCULAR INFUSION OF BEEF CARCASSES

INTRODUCTION

The description of flow patterns in a continuous flow system has been found very useful for predicting chemical reactor output. Two ideal flow patterns are generally recognized: plug flow and perfect mixing (Levenspiel, 1979). However, deviations occur in most real systems. Although heat transfer during vascular infusion can be described using a heat exchanger model (Chapter 3), the flow behavior within the vascular system is poorly understood. The development of improved heat transfer models for vascular infusion requires a better understanding of flow pattern and residence time distribution of chilling fluid within the vascular system. This can be achieved by introducing a tracer pulse at the fluid inlet and analyzing tracer concentration as function of time in the outlet stream.

Tracers used to study residence time distribution should be non reactive with fluid in the flow system and must not be lost from the flowing phase (Froment and Bischoff, 1991). Choice of a suitable dye is very important to obtain correct residence time distribution curves. Evans Blue (T-1824) has been widely used to estimate plasma volume in vascular systems for many years, since it only disappears very slowly from the bloodstream, its color is well suited to colorimetric detection, and it forms stable solutions

(Harington *et al.*, 1940). Evans Blue is an azo dye having both amino and sulphonic acid groups in its molecule. The sulphonic acid groups are present in larger amounts and it is therefore expected that the dye will be extractable from aqueous solution into a partially miscible organic solvent.

The aim of this work is to determine flow patterns within the vascular system using a trace pulse method.

MATERIALS AND METHODS

Determination of Residence Time Distribution (RTD)

Three cull cows with different live weights were assigned to this experiment. The animals were slaughtered and bled by severing the jugular veins. About 10 blood samples were collected by 10 ml heparinized vacutainers (Becton Dickinson of Canada Inc., Mississauga, ON) prior to infusion of pre-chilled water. The blood samples were kept in an ice bucket to prevent hemolysis, and were used to provide pure plasma for later sample analysis.

Pre-chilled water was pumped into the vascular system through a catheter inserted into the left carotid artery. Based on animal size and total volume of infused water, a difinite amount of tracer T-1824 (Evans Blue, BDH Chemicals Canada Ltd., Edmonton, AB, Canada) ranging from 100 to 400 mg was dissolved in about 15 ml of 0.9% NaCl solution and drawn into an injection syringe. As water infusion started, a pulse of tracer was injected into the fluid entering the vascular system through the catheter inlet. The syringe was weighed before and after injection to determine the exact amount of tracer delivered. Effluent samples used for subsequent tracer determination were collected

manually from the exit stream at regular intervals. Plasma was extracted from the blood samples by centrifugation and determination of dye concentration in effluent samples was carried out as follows.

Two 1.0 ml aliquots of pure plasma and dye-stained fluid were accurately pipetted into 12 × 75 mm Pyrex test tubes. Exactly 0.2 ml of 0.85% NaCl solution was added to each dye-stained sample and one of the blank plasma samples. A standard was prepared from the remaining blank plasma sample by addition of a known amount of dye dissolved in 0.2 ml of 0.85% NaCl solution. The contents of the tubes were then mixed using a votex mixer and 3.0 ml of reagent grade acetone was pipetted into each tube. The tubes were covered with Parafilm immediately after addition of acetone and shaken vigorously in a votex mixer for 10 seconds. Then, the Parafilm covered tubes were centrifuged for 10 min. at 1200g using an Omnifuge RT centrifuge. The supernatant solutions containing most of the dye were transferred to 12 × 75 mm Pyrex test tubes. The tubes were sealed with Parafilm and then centrifuged for another 10 min. at 1200g to remove any suspended protein particles. The clear supernatant solutions were pipetted into cuvettes (Fisher Scientific, Edmonton, AB, Canada) and sealed with Parafilm to prevent evaporation of acetone. Dye concentration was determined using a spectrophotometer (PU 8625 UV/VIS). Absorption was measured at 620 nm, and compared against a standard curve covering dye concentrations from 1 to 50 mg/l.

Three different flowrates were used in these preliminary trials, and carcass weight changes were monitored manually during infusion. After infusion, carcasses were subjected to normal skinning and evisceration procedures to observe the dye distribution in different parts of the animal.

Total volume of water infused during the tracer pulse experiments varied from 71 to 100 kg, depending on animal live weight. Absorption of dye by the meat was minimized by using low infusion pressures and flowrates ranging from 7.6 to 11.5 l/min.

Calculation of Mean RTD from Experimental Data

Based on experimental tracer concentrations in the outlet stream as function of time, the residence time distribution, E(t), can be obtained from the following equations:

$$E(t) = \frac{C(t)}{\int_0^\infty C(t)\,d(t)} \qquad (4.1)$$

$$M = \int_0^\infty F\,C(t)dt \qquad (4.2)$$

The theoretical mean residence time is:

$$\bar{t} = \frac{V}{F} \qquad (4.3)$$

where:

$C(t)$ = tracer concentration in outlet stream (mg/l)

F = medium flowrate (l/s)

M = total amount of tracer injected (mg)

V = total volume of the vascular system (l)

The experimental mean residence time, $\bar{t}_a$, can be calculated from (Bischoff and McCracken 1966):

$$\bar{t}_a = \int_0^n \theta\, E(\theta)d\theta \qquad n \cong 2, 3 \qquad (4.4)$$

$$\theta = t / \bar{t} \tag{4.5}$$

$$E(\theta) = \bar{t}\, E(t) \tag{4.6}$$

In Eq. (4.4), the integral does not extend to infinite since real vessels deviate from ideal flow and truncation is necessary to minimize prediction errors.

RESULTS AND DISCUSSION

Tracer test results for vascular infusion of 3 cull cows are presented in Tables 4.1 through 4.3. The weight gain of beef carcasses during infusion is a linear function of time, as described in chapter 3. The effluent can be considered as flowing into two reservoirs, one of which being the outside container and the other being an inside reservoir resulting from the abdominal cavity and enclosed organs. Consequently, the mass balance for the tracer was based on the constant inlet and outlet flowrates.

The residence time distribution curves (RTD) are shown in Figures 4.1 to 4.3. The theoretical mean residence time is based on the assumption of the total vascular volume being 7.0% of animal live weight, which is an average value from the literature (Frandson, 1974 and Swenson, 1977). All experimental results show that measured mean residence times are lower than the theoretical values. This indicates that there is a dead or wasted space in the vascular system which is inaccessible to the flow medium. Also, the wide spread of RTD curves means that axial dispersion (mixing) of infusion fluid within the vascular system is significant. Thus, the flow pattern within the vascular system can be conceptually described as plug flow with axial dispersion and dead space.

The residence time distribution in Figure 4.1 can be modeled as schematically shown in Fig. 4.4. Unlike Fig. 4.1, Figs. 4.2 and 4.3 show two distinct peaks. This behavior can be interpreted as two parallel vessels with axial dispersion and dead space. The theoretical flow model for this case is shown in Fig. 4.5 (Levenspiel, 1979).

The overall mean residence time was calculated as the combined volume of the two vessels divided by the total flowrate through both vessels. Because $t_a < t$, there should be a dead volume within the vascular system. Also, the spread between peaks suggests the existence of axial dispersion. The first peak in Figs. 4.2 and 4.3 appears shortly after injection, which means the first vessel is much smaller than the second one.

Visual observation of carcasses after skinning and evisceration revealed that retained water in the muscles remained mostly in the vascular system, very close to the surface. This excess water (rather than original carcass water) was lost by evaporation in the chiller, thus substantially reducing or eliminating net carcass shrink.

CONCLUSIONS

Vascular infusion of beef carcasses can be described by a flow model consisting of two parallel vessels of different volume plus a relatively small dead volume. Flow behaviour of infused water through each parallel vessel is plug flow with axial dispersion. The volume of the smaller vessel is independent of animal weight and may represent a bypass circuit through the heart. The larger vessel can be related to the vascular network extending into the body and extremities, and its volume is directly related to the animal weight. Absence of the first peak at the lower infusion rate (Fig. 4.1) is probably due to insufficient pressure to force a bypass through the heart.

Table 4.1. Calculation of residence time distribution from experimental data for 190 kg animal at flowrate of 7.6 l/min.

Time (s)	C(t) (mg/l)	E(t) x 10^3 (1/s)	θ E(θ)
0	0	0	0
30	1.32	1.20	0.010
45	4.60	4.19	0.027
60	7.25	6.60	0.056
75	10.40	9.47	0.10
90	17.33	15.78	0.20
105	12.29	11.19	0.17
120	8.51	7.75	0.13
135	5.86	5.33	0.10
150	3.09	2.81	0.060
165	1.45	1.32	0.031
180	1.01	0.91	0.023
195	0.93	0.82	0.021
M = 139.1 mg		$\Sigma\theta E(\theta) = 0.92$	
Theoretical mean $\bar{t} = 105(s)$		Calculated mean $\bar{t}_a = 97.2(s)$	

Table 4.2. Calculation of residence time distribution from experimental data for 290 kg animal at flowrate of 10.0 l/min.

Time (s)	C(t) (mg/l)	E(t) x 10^3 (1/s)	θ E(θ)
0	0	0	0
15	3.47	2.31	0.0043
30	16.71	11.15	0.041
45	0.95	0.63	0.0035
60	5.99	4.00	0.030
75	11.66	7.78	0.072
90	13.55	9.04	0.10
105	11.28	7.53	0.097
120	8.63	5.77	0.085
135	7.12	4.76	0.079
150	5.10	3.41	0.063
165	3.47	2.31	0.047
180	3.22	2.15	0.048
210	3.09	2.06	0.106
240	0.95	0.60	0.037
M = 250.0 mg		$\Sigma\theta E(\theta) = 0.81$	
Theoretical mean $\bar{t}_a = 121.8(s)$		Calculated mean $\bar{t}_a = 98.6(s)$	

Table 4.3. Calculation of residence time distribution from experimental data for 520 kg animal at flowrate of 11.5 l/min.

Time (s)	C(t) (mg/l)	E(t) x 10^3 (1/s)	θ E(θ)
0	0	0	0
15	5.99	2.79	0.0033
30	14.82	6.89	0.016
60	0.05	0.02	0.00011
75	0.32	0.15	0.00087
90	0.95	0.44	0.0031
120	5.74	2.67	0.051
135	7.25	3.37	0.036
165	11.29	5.25	0.14
180	10.40	4.84	0.069
210	9.77	4.54	0.16
240	7.13	3.37	0.13
270	5.49	2.55	0.11
300	3.47	1.61	0.076
330	2.85	1.32	0.069
360	1.96	0.91	0.051
M = 389.3 mg		$\Sigma\theta E(\theta) = 0.89$	
Theoretical mean $\bar{t} = 198.5(s)$		Calculated mean $\bar{t}_a = 170.2(s)$	

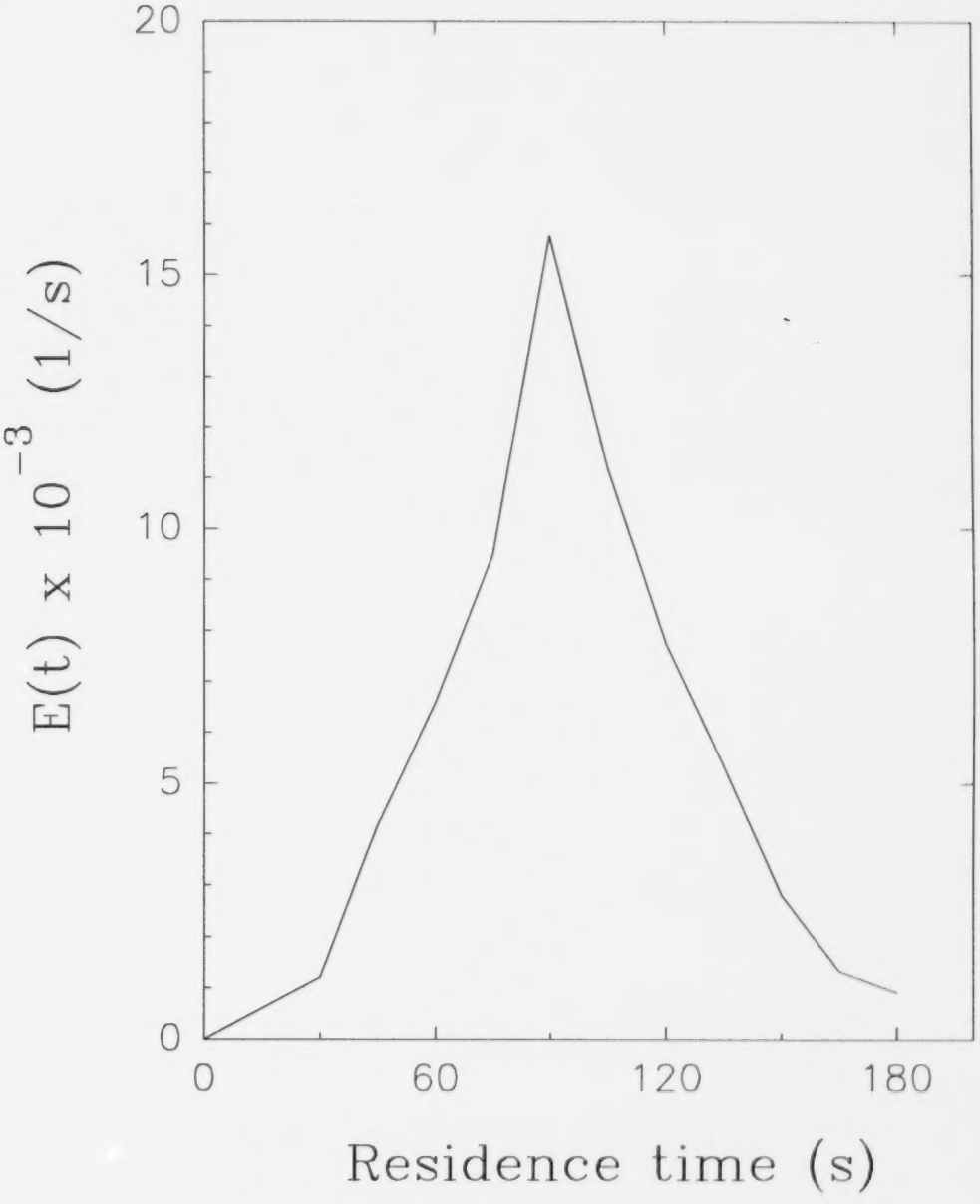

Figure 4.1. Residence time distribution for 190 kg animal at flowrate of 7.6 l/min.

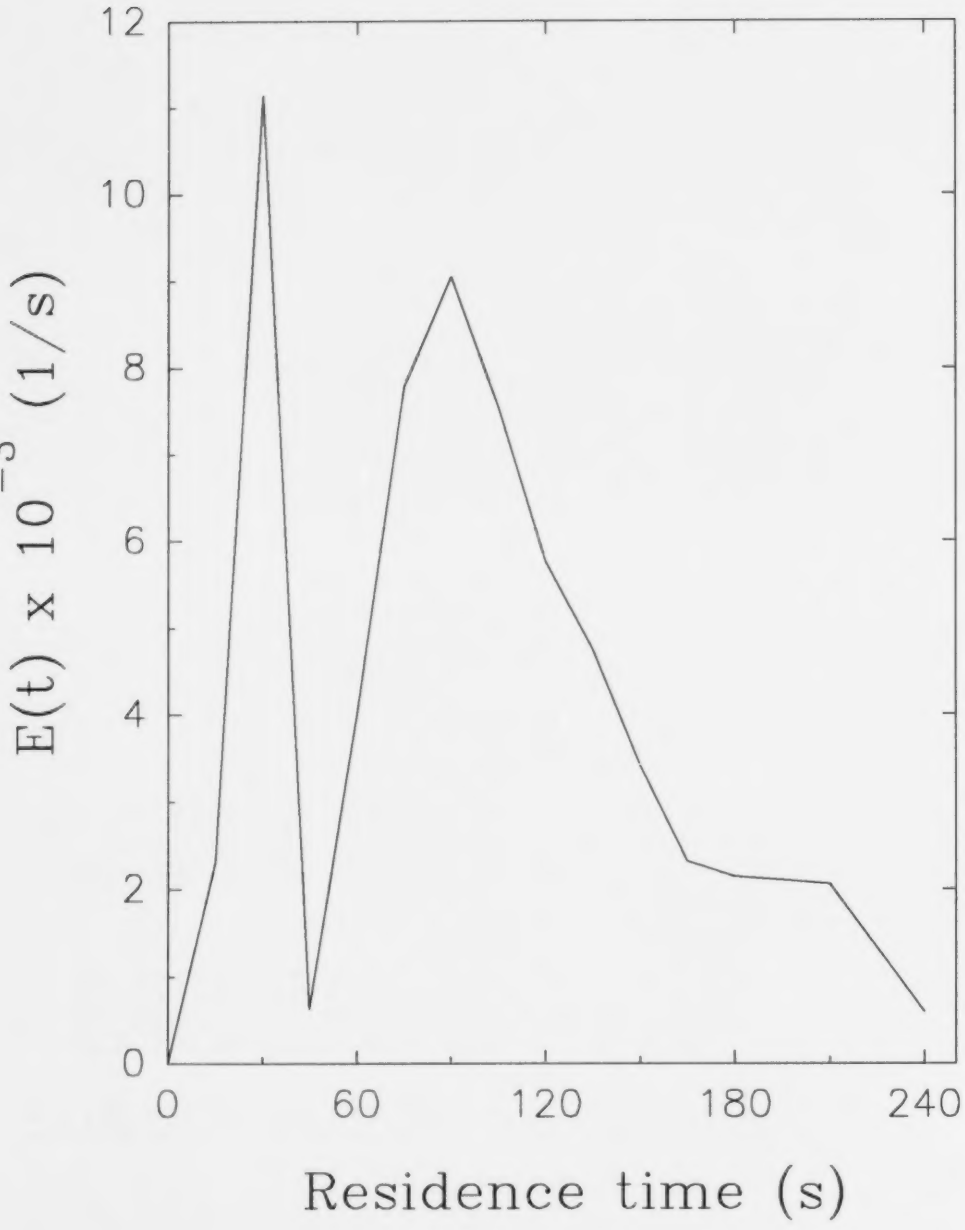

Figure 4.2. Residence time distribution for 290 kg animal at flowrate of 10.0 l/min.

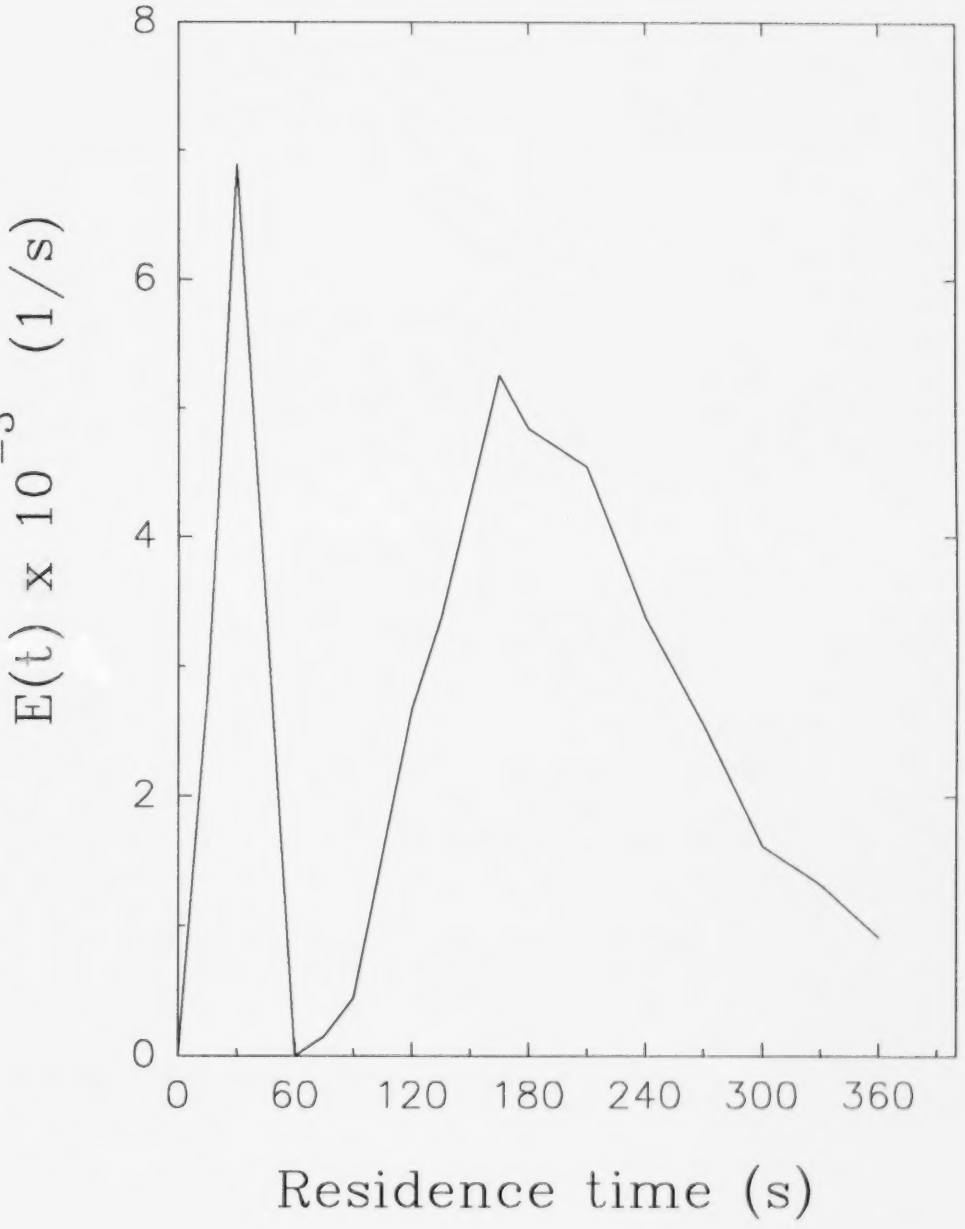

Figure 4.3. Residence time distribution for 520 kg animal at flowrate of 11.5 l/min.

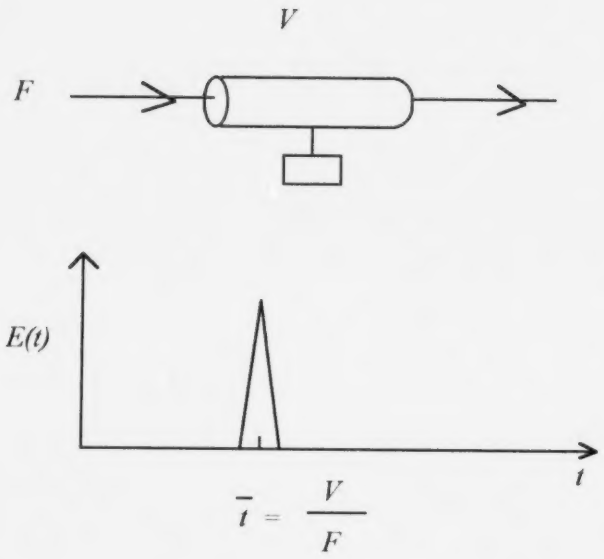

Figure 4.4. Single-vessel plug flow model.

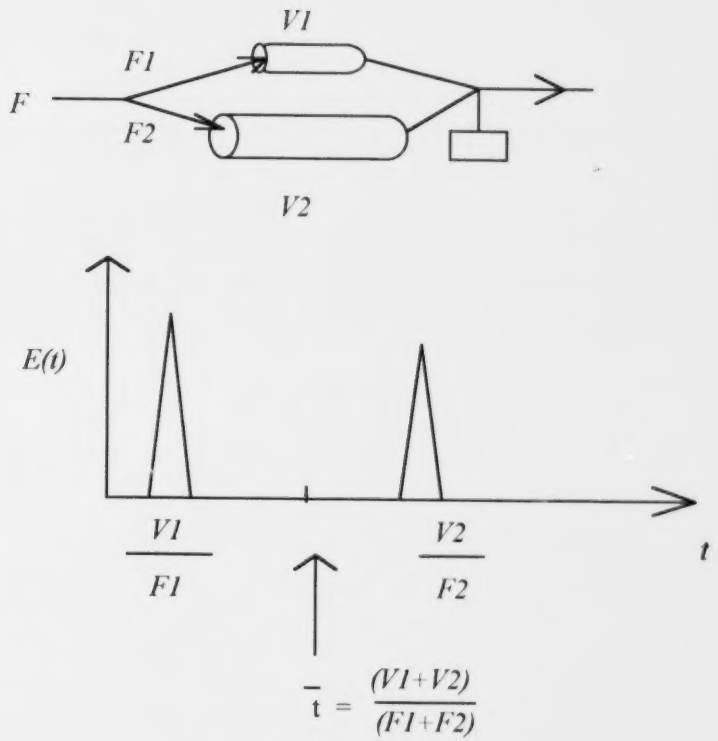

Figure 4.5. Parallel-vessel plug flow model.

REFERENCES

Bischoff, K.B. and McCracken, E.A. 1966. Tracer tests in flow systems. *Ind. Eng. Chem.* **58**(7): 18-31.

Chinard, F.P. 1951. Estimation of plasma volume by dye dilution method. In *Methods in Medical Research.* Vol. 4. Vissher, M.B.(Ed.). The Year Book Publishers, Chicago, pp. 38-48.

Frandson, R.D. 1974. Blood and other body fluids. Ch. 13 In *Anatomy and Physiology of Farm Animals.* 2th Edition, Frandson, R.D. (Ed.). Lea & Febiger Inc., Philadelphia, pp.174-189.

Froment, G.F and Bischoff, K.B., 1991. *Chemical Reactor Analysis and Design*. Wiley Series in Chemical Engineering. John Wiley & Suns Inc., NY, pp. 509-563.

Harington, C.R., Pochin, E.L. and Squire, J.R. 1940. A simplication of the Evans Blue method of blood volume determination. *Clin. Sci.* **4**: 311-321.

Levenspiel, O. 1979. *The Chemical Reactor Omnibook* . OSU Book Store Inc., Corvallis, OR 97330.

Swenson, M.J. 1977. Blood circulation and the cardiovascular system. Ch. 2 in *Dukes' Physiology of Domestic Animals.* Swenson, M.J. (Ed.). Comstock Publishing Inc., London, pp.14-35.

CHAPTER 5

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The work carried out in this study revealed that vascular infusion of cold water accelerated the early postmortem chilling rate of beef carcasses. Experimental results showed that vascular infusion of intact beef carcasses substantially increased LD muscle chilling rates, but had little effect on deep SM muscle. Flowrate had no noticeable influence on the chilling rate because the total volume of infused water was fixed at 10 and 20% of animal live weight. Thus, the higher the flowrate the shorter the contact time between water and carcass.

Heat and mass transfer during vascular infusion was characterized using an engineering model. The model adequately predicted time-temperature profiles of intact muscle based on known fluid temperature, flowrate, infusion time and carcass size. The average temperature of intact carcasses subjected to vascular infusion of 1^{o}C water totalling 10 and 20% of animal live weight was reduced to 37.3 and 35.0^{o}C, respectively. With infusion of 10^{o}C water totalling 20% of animal live weight, the final muscle temperature was 36.4^{o}C. Similarly, the fraction of thermal energy removed by vascular infusion of 1^{o}C water at a level of 10 and 20% of animal live weight was 7.9 and 14.3%, respectively. Approximately 10.9% of the total thermal energy in carcasses was removed by vascular infusion of 10^{o}C water at a level of 20%.

Carcass shrinkage during conventional chilling were substantially reduced by vascular infusion of water. The total volume infused into carcasses was the main factor

influencing water retention, while infusion flowrate only had a marginal effect on water retention within the muscle. Carcass sides infused with 1°C water at a level of 10 and 20% of animal live weight gain about 2 and 4% water, respectively, compared with control sides subjected to conventional abattoir procedures. Most of the weight gained by carcass sides was likely due to superficially retained water which was removed by evaporation in the cooler, resulting in negligible net weight loss even over a 6-day aging period.

Visual observation of intact carcasses during infusion suggested that a minimum flowrate of about 12 to 15 l/min was necessary to achieve adequate water circulation to all parts of the carcass, particularly the hind limb. Though increasing flowrate beyond this level may improve carcass temperature distribution and increase chilling rates (if the fluid contact time is kept constant, independently of flowrate), higher flowrates might excessively increase total water uptake and affect meat quality.

It was observed that pumping 10°C water through the vascular system required less mechanical energy than 1°C water, since water with milder temperature could more readily open collapsed arteries and veins during infusion. The friction factor obtained from a momentum balance can be used to estimate the pump pressure required to achieve uniform internal flow distribution and effective heat transfer between the intact carcass and infusion medium.

Flow patterns within the vascular system, as revealed by a limited number of tracer dye experiments, were characterized as plug flow with axial dispersion and dead space, with either one vessel or two parallel vessels. The minor difference in the flow behaviour represented by these two models is possibly a consequence of the different infusion flowrates. Residence times obtained from experimental residence time distribution curves

were very close to theoretical values, suggesting that pre-chilled water effectively reached all parts of the carcass, exerting the desired chilling effect on hot muscle.

In addition to the benefits resulting from increased overall chilling rate and reduced weight loss, a major advantage of the proposed vascular infusion technology is that it can be adapted to existing meat processing plants without need for expensive renovations.

The present study provides useful information on this novel vascular infusion technology. However, more work is necessary to fully assess the effects of infusion medium and different infusion temperatures on overall meat quality. The study of the effect of carcass orientation and carcass size, as well as infusion flowrates above 15 l/min at constant infusion time, may also provide valuable information beyond that presented in this work. This research could be also expanded to study the effects of vascular infusion of solutions containing food-grade solutes, such as vitamins sugars and proteolytic enzymes, on postmortem rigor and meat quality.